Reionization and the CMB

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UC Berkeley / LBL

PICO Workshop, University of Minnesota

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Cosmic Structure

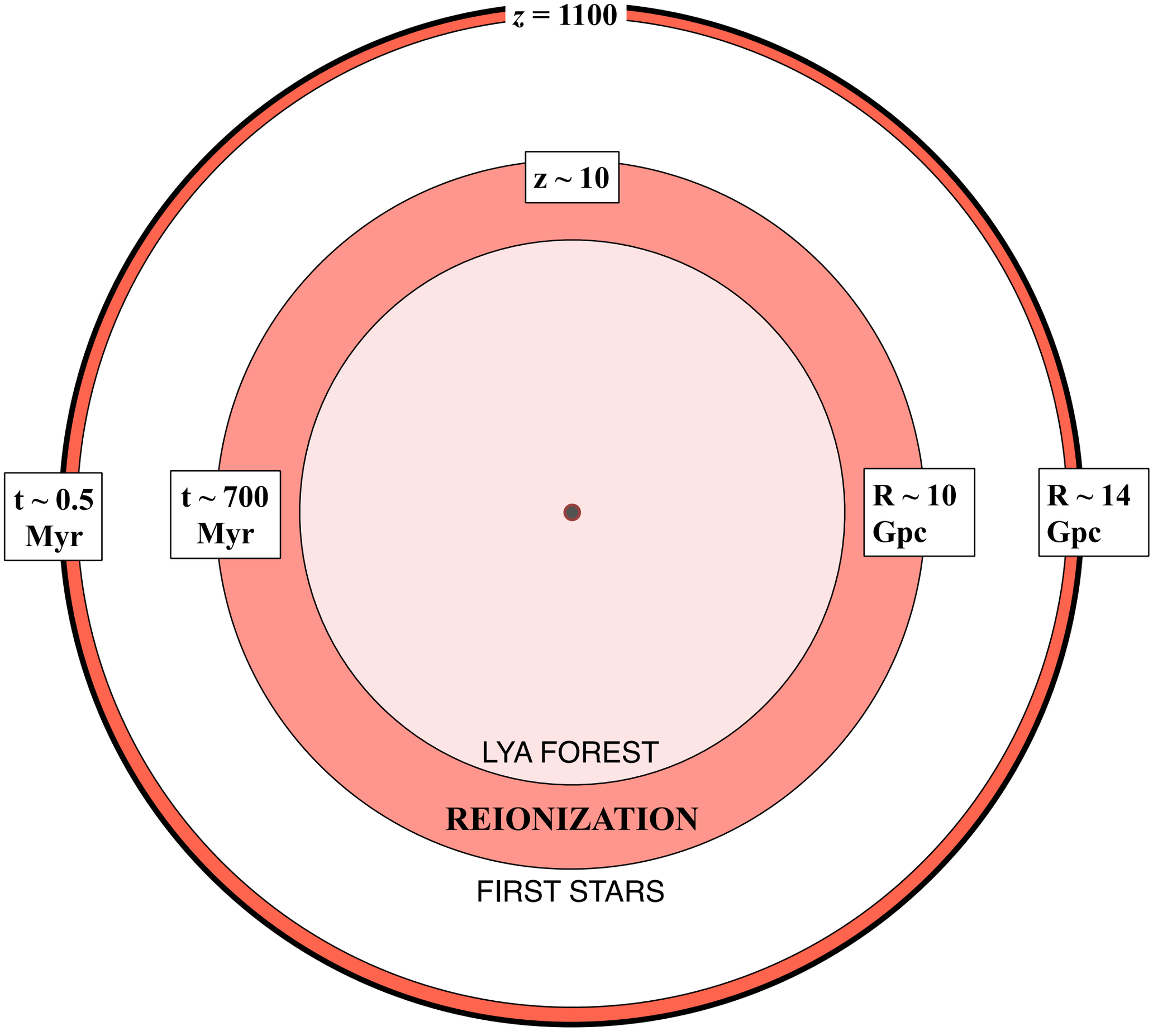
Dark Matter and Inflation

Emergence of Galaxies

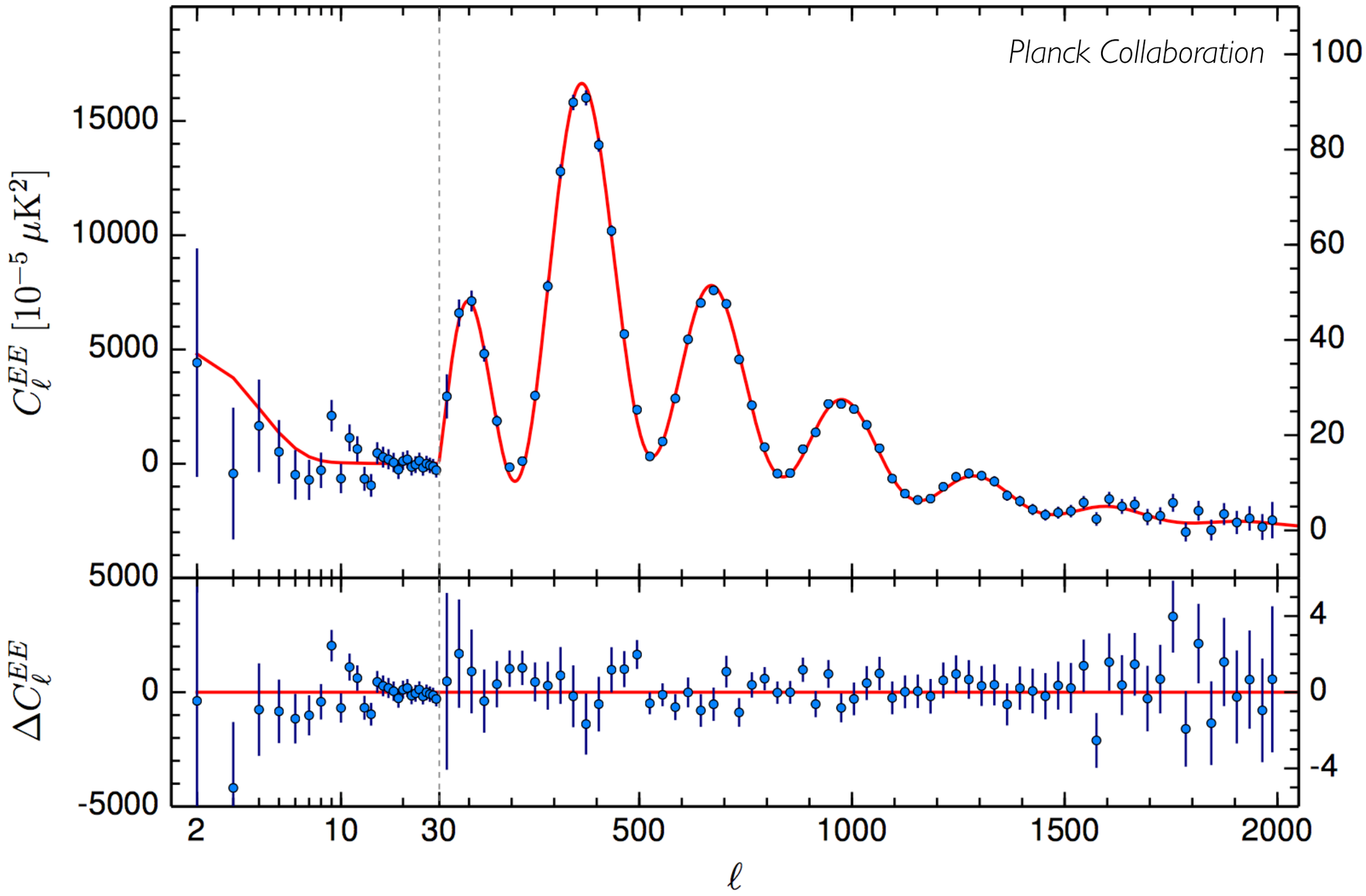
First Stars and Black Holes

Intergalactic Medium

Heating and Enrichment


z = 1100
z ~ 10
t ~ 0.5 Myr
t ~ 700 Myr
R ~ 10 Gpc
R ~ 14 Gpc
LYA FOREST
REIONIZATION
FIRST STARS

CMB Polarization "Reionization Bump"



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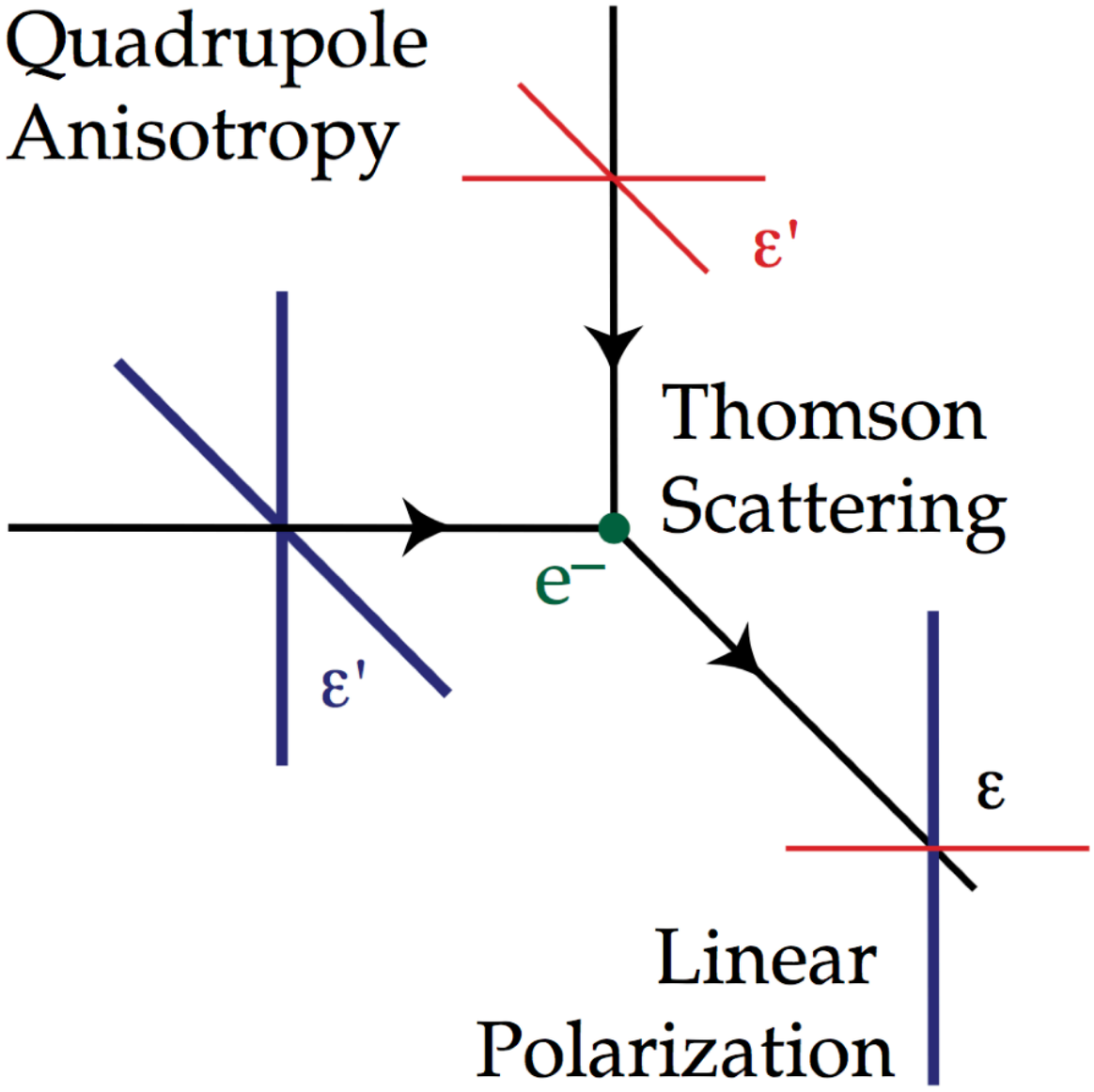
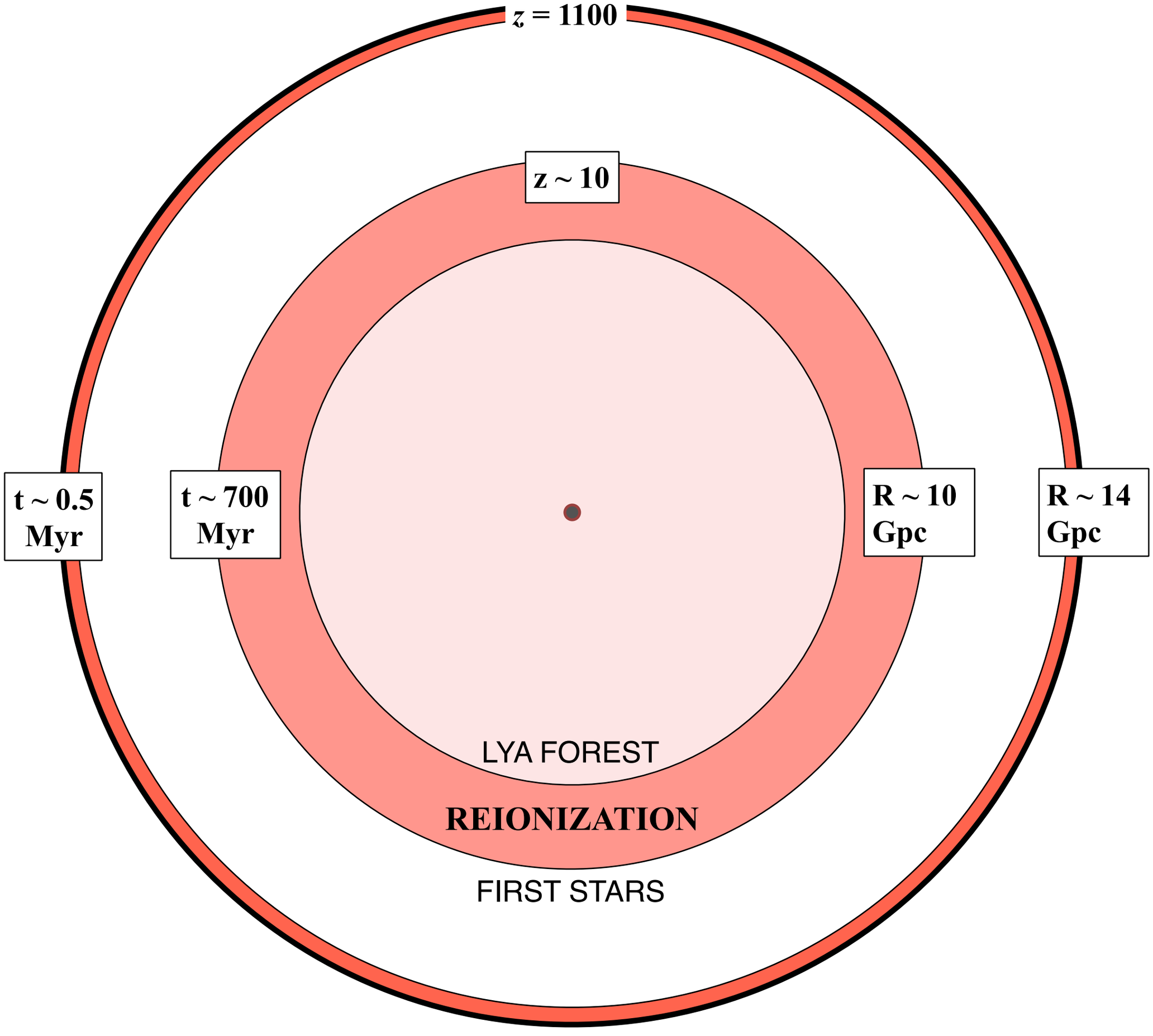


W. Hu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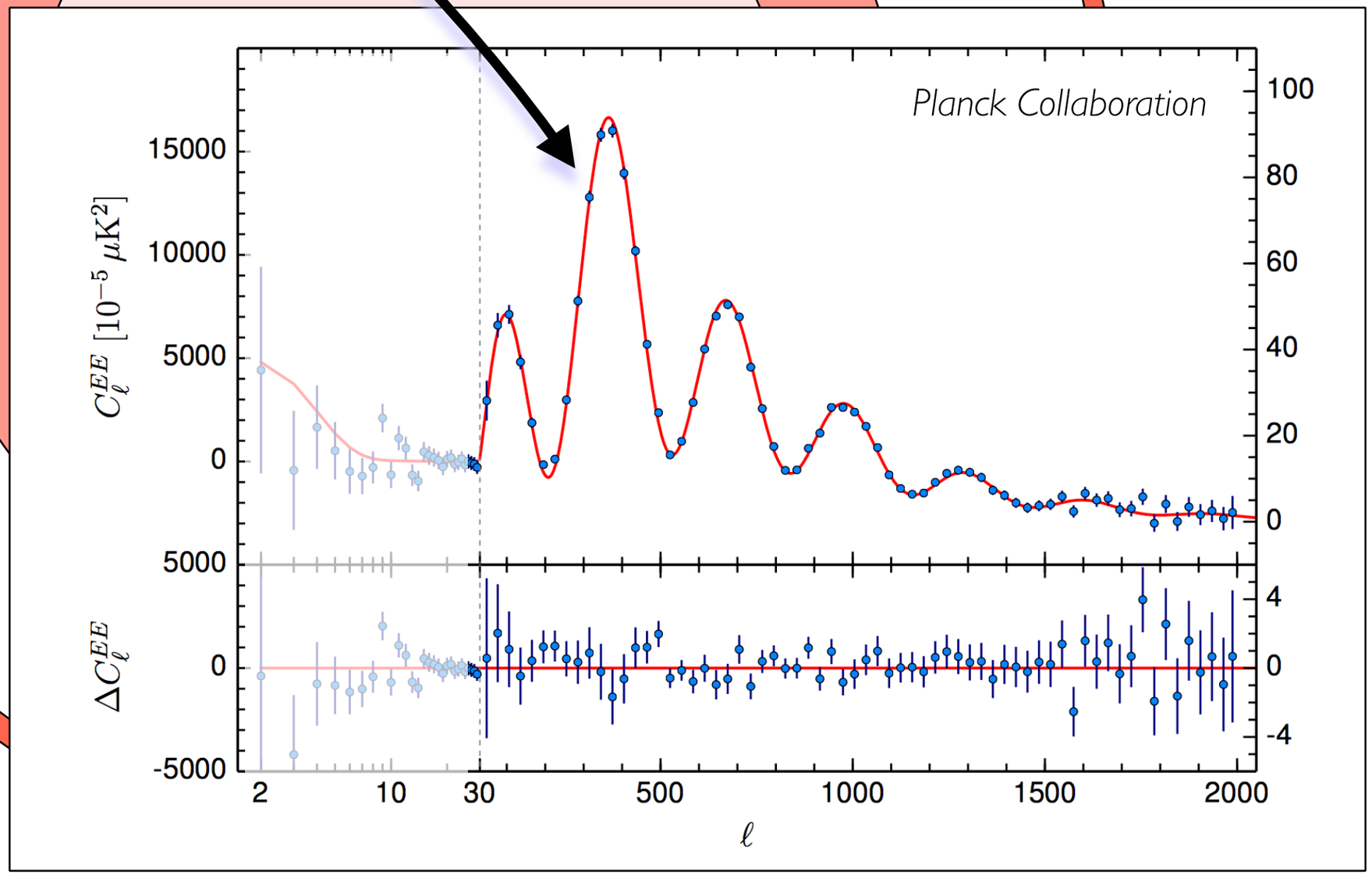

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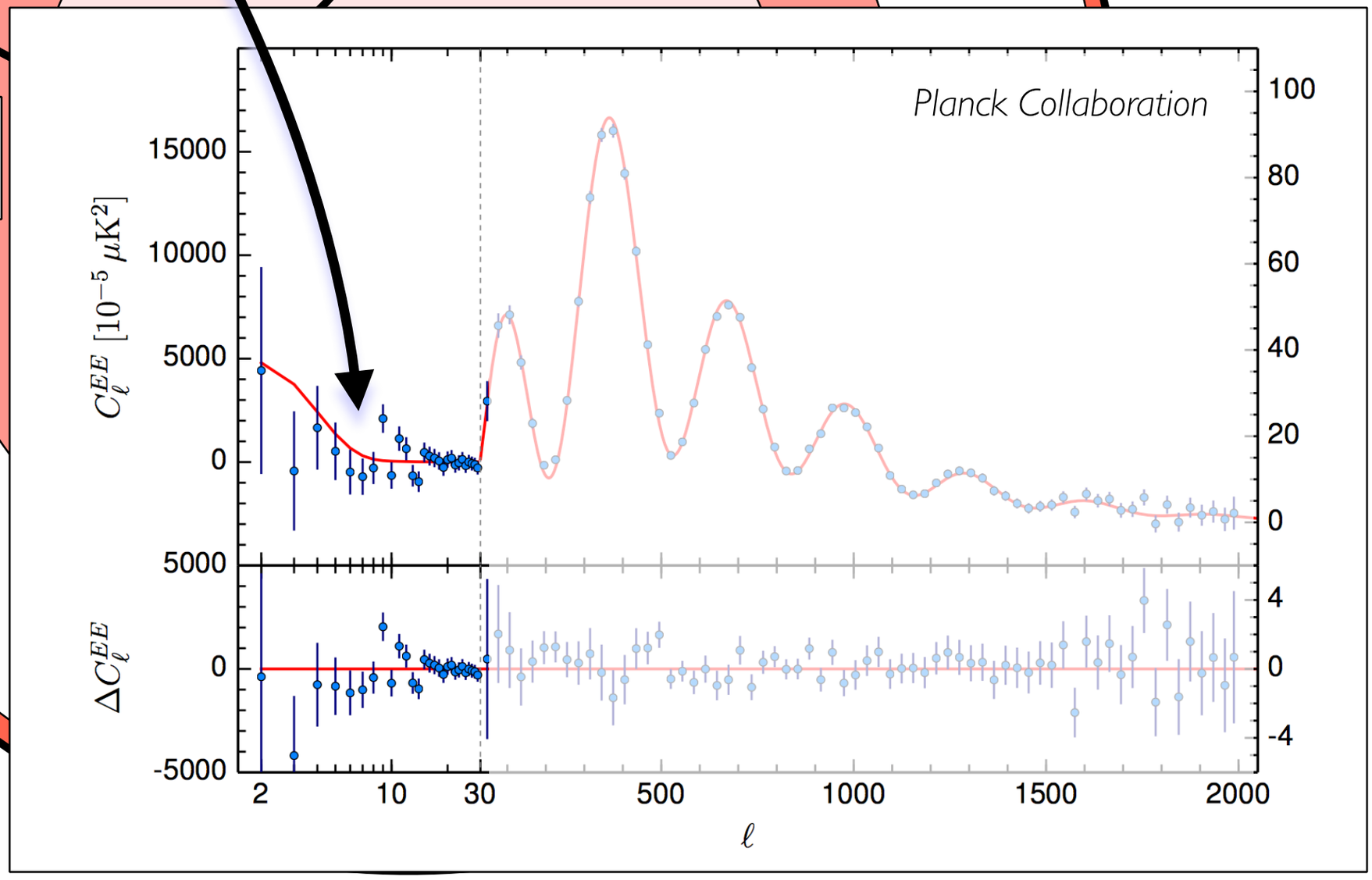
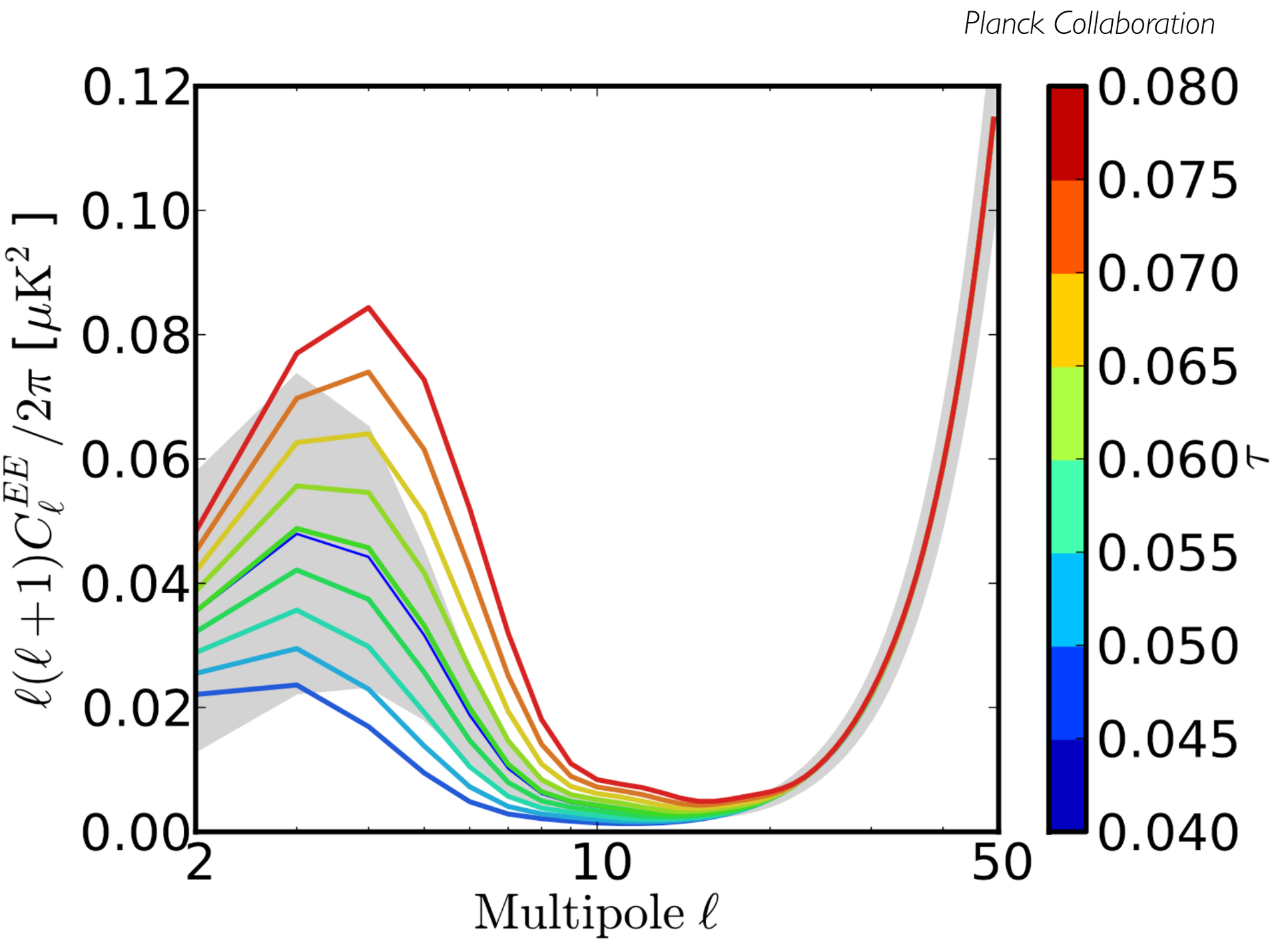
t ~ 700 Myr

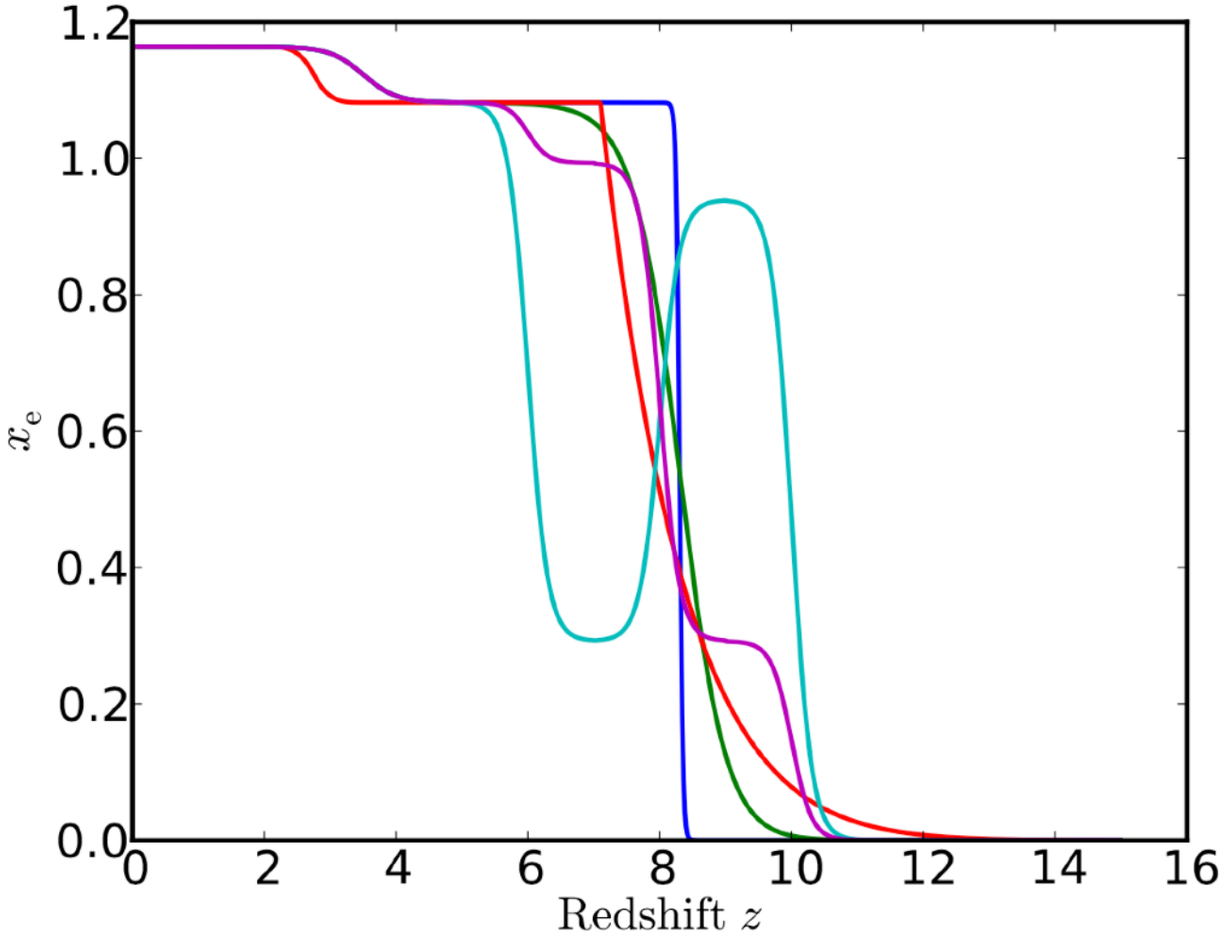

Planck Collaboration
15000
10000
5000
0
5000
0
-5000
C_ℓ^{EE} [10^{-5} μK^2]
ΔC_ℓ^{EE}
100
80
60
40
20
0
4
0
-4
2
10
30
500
1000
1500
2000
ℓ

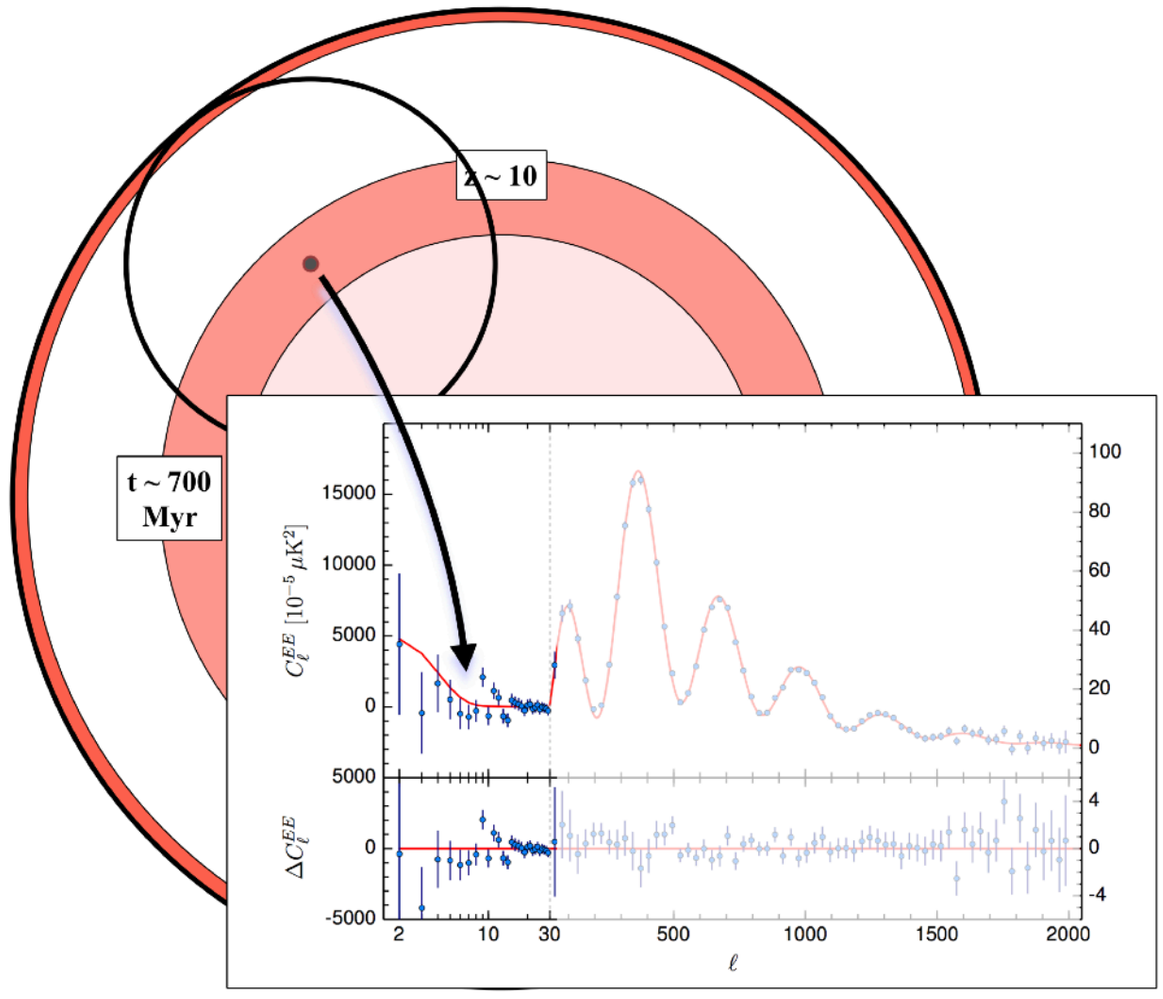
Measuring τ with the Reionization Bump



Measuring τ with the Reionization Bump

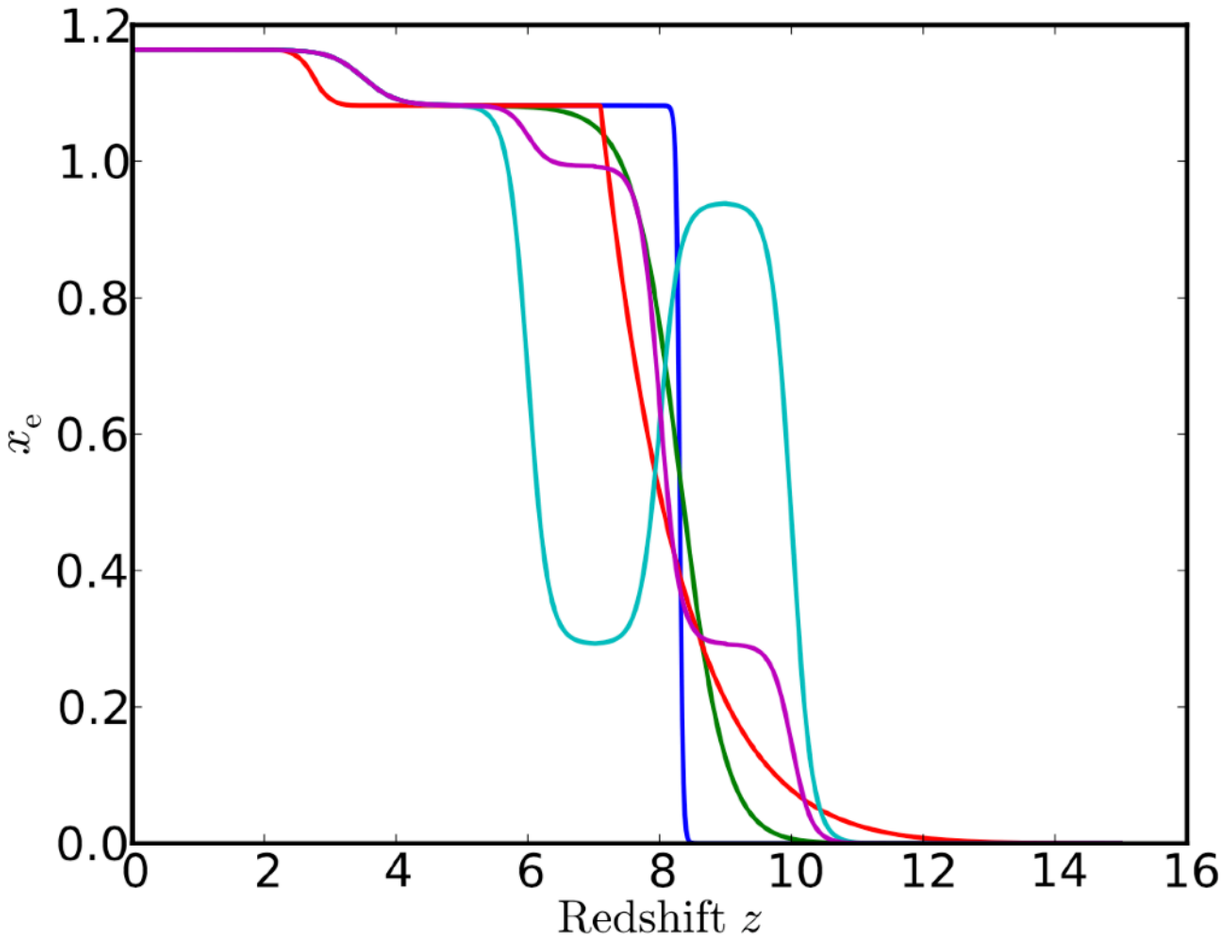
Planck Collaboration

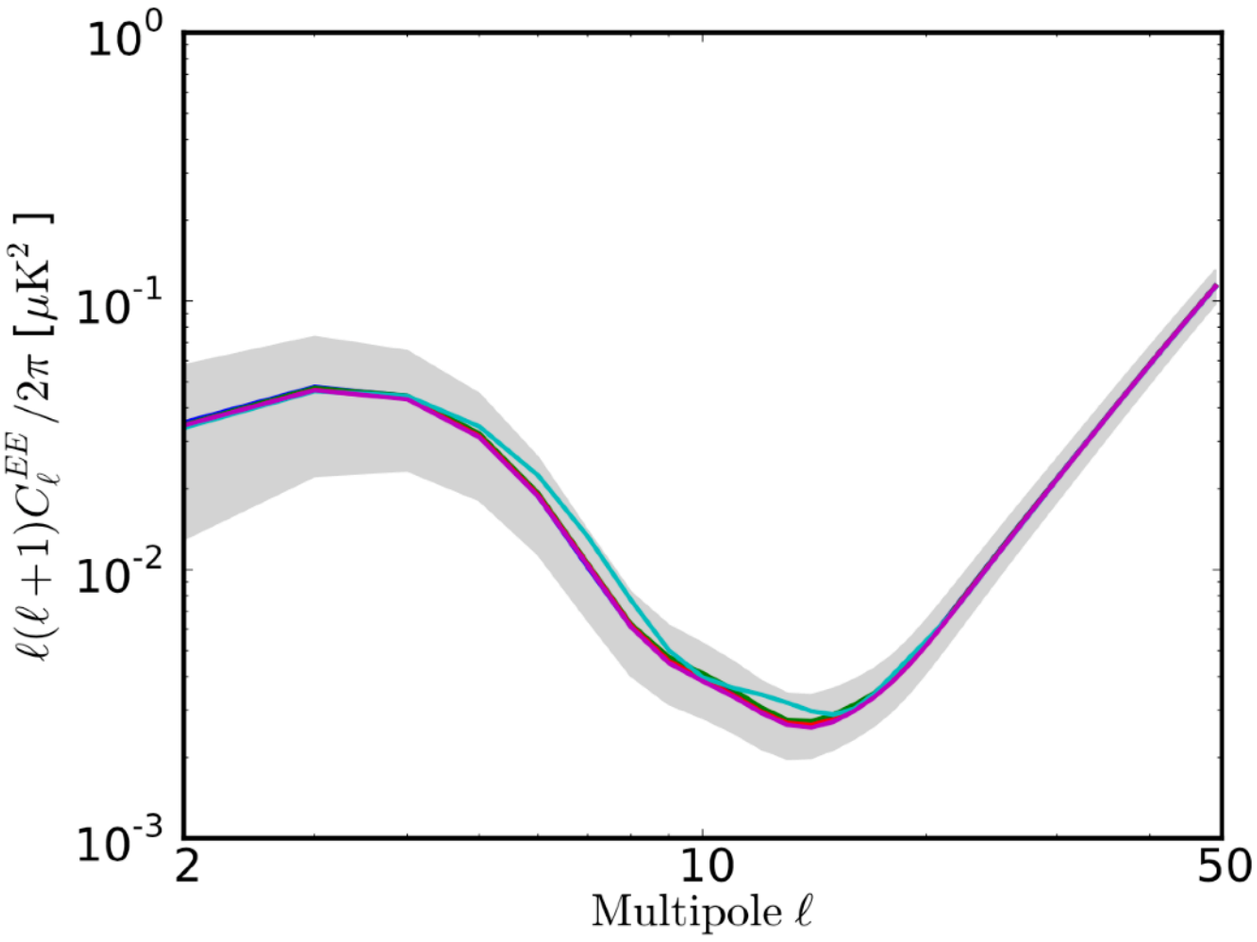




Measuring τ with the Reionization Bump

Planck Collaboration

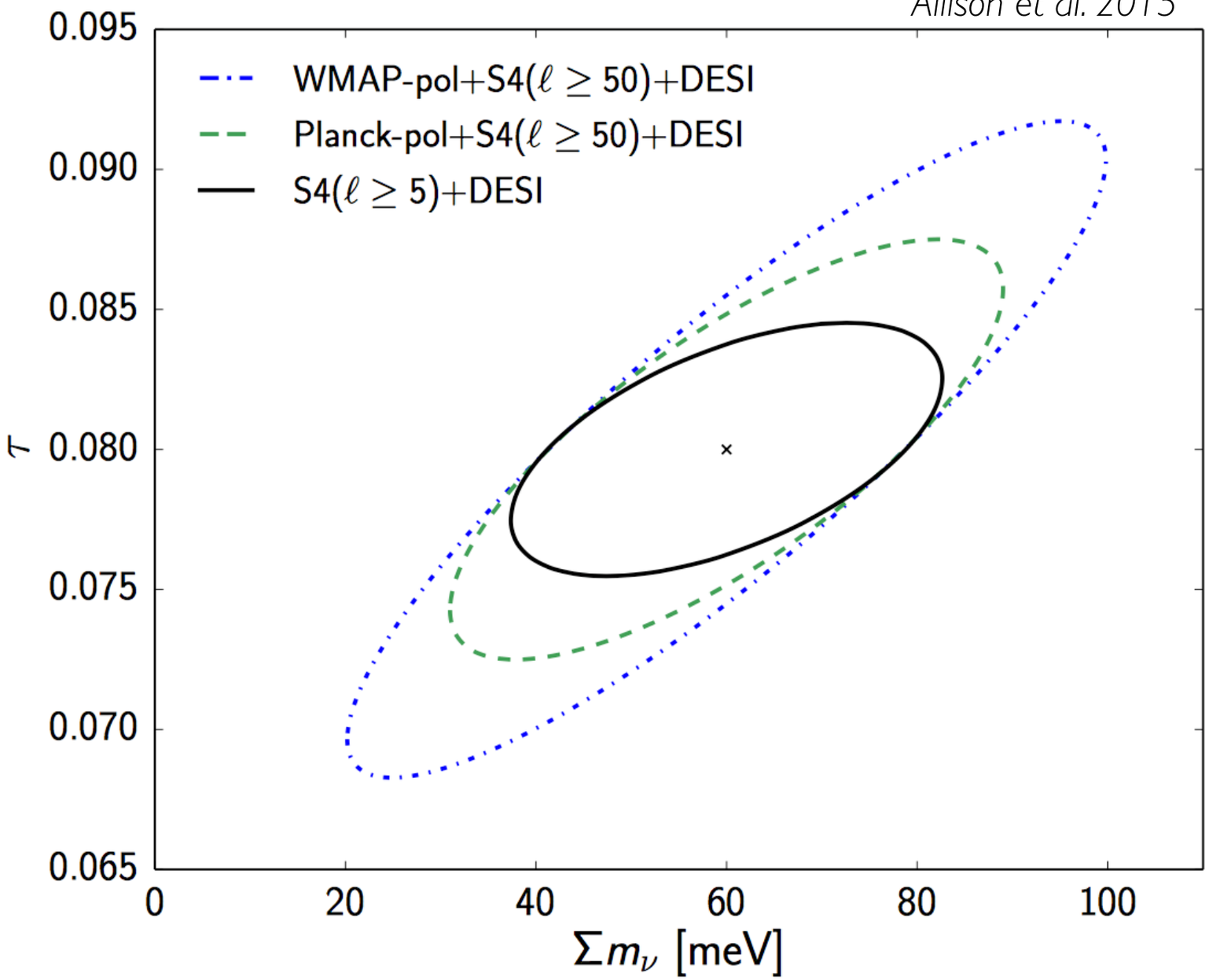




Measuring τ with the Reionization Bump

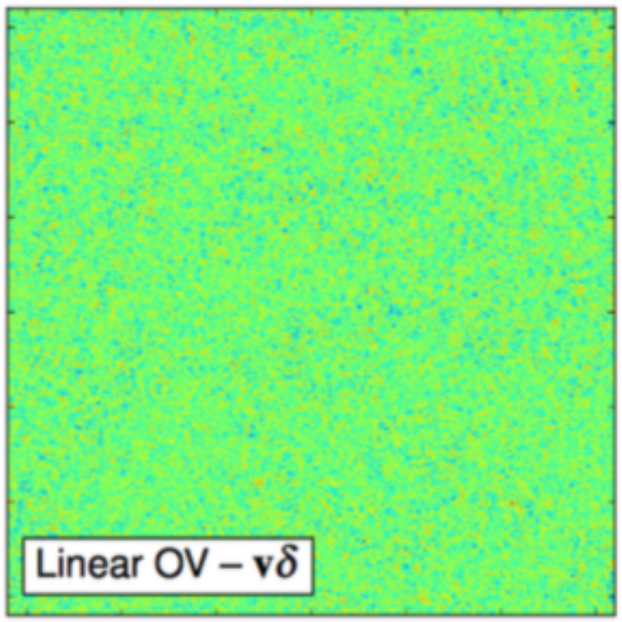
Reduces uncertainty in CMB constraints on amplitude of primordial fluctuations

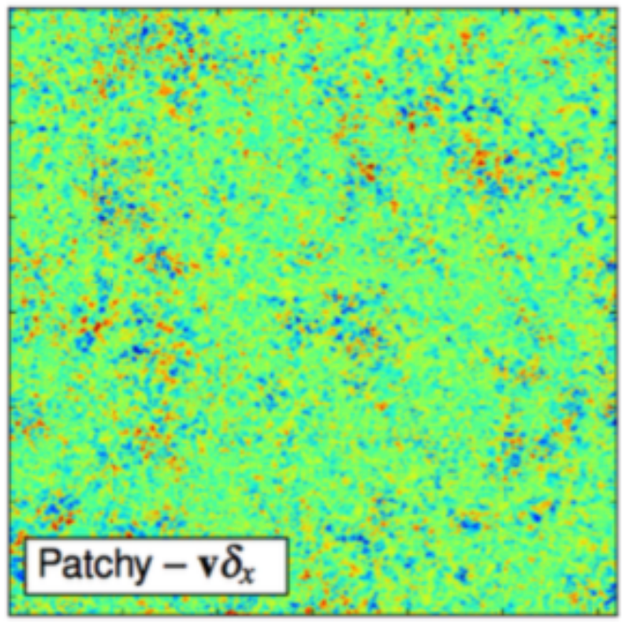
Allison et al. 2015

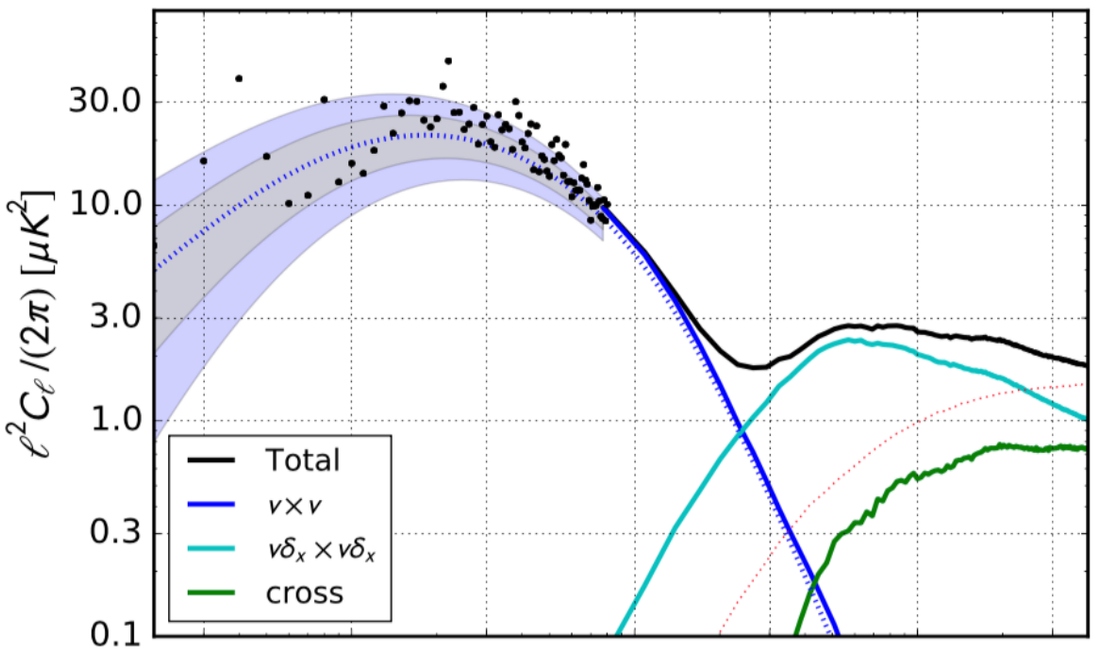


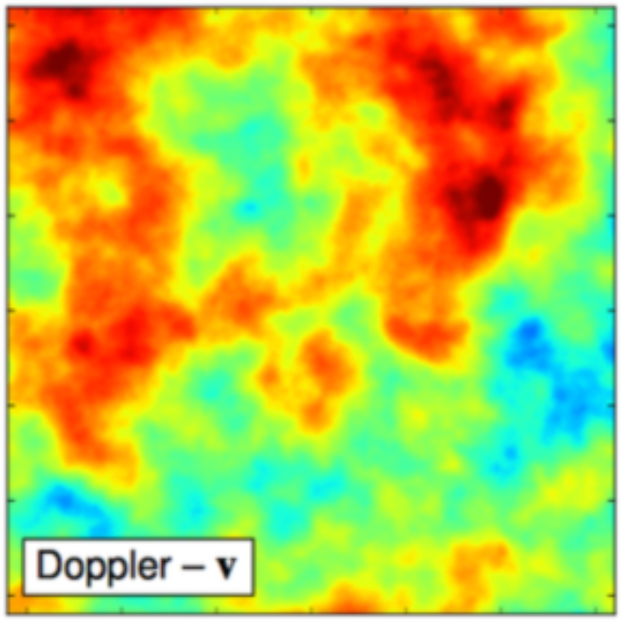
kSZ from Patchy Reionization

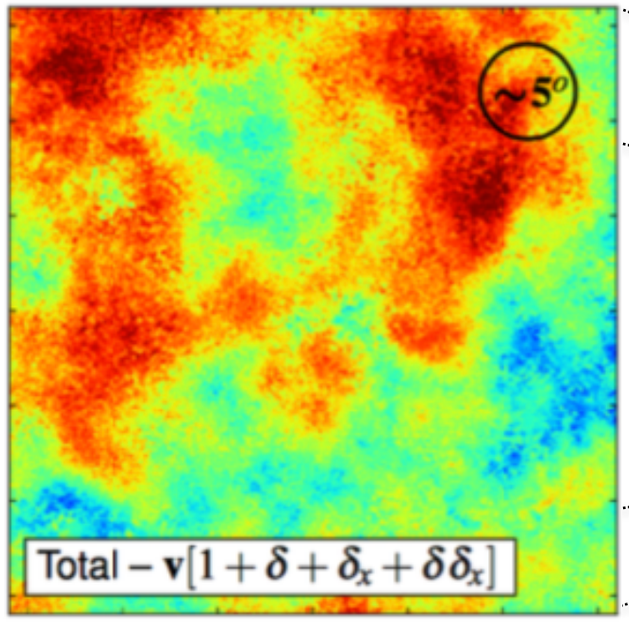
Alvarez (2016)

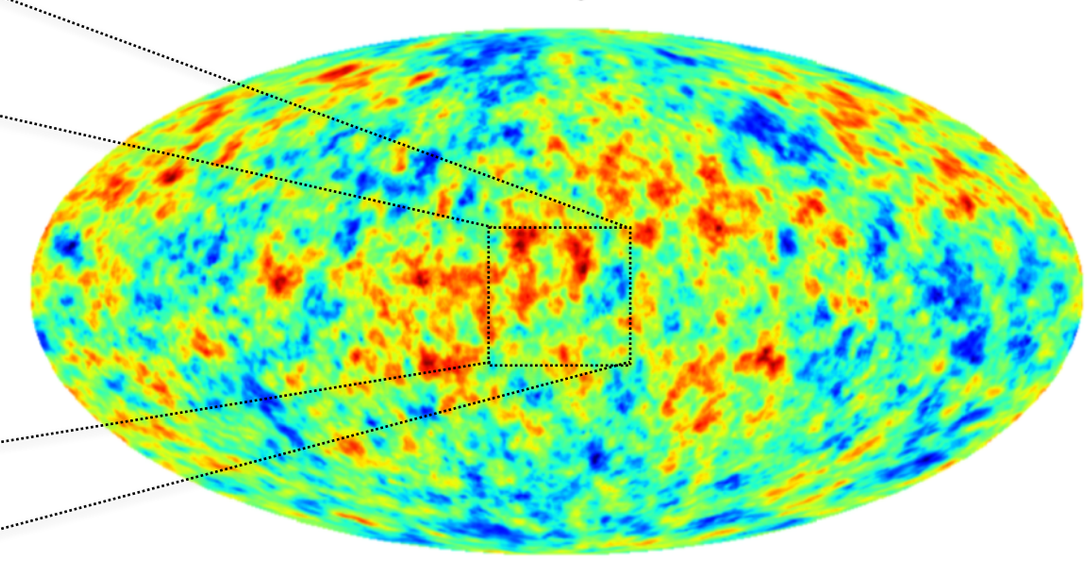


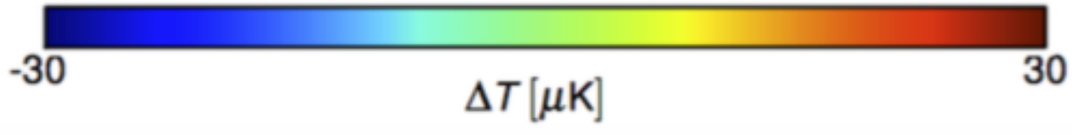


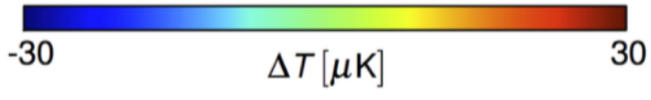


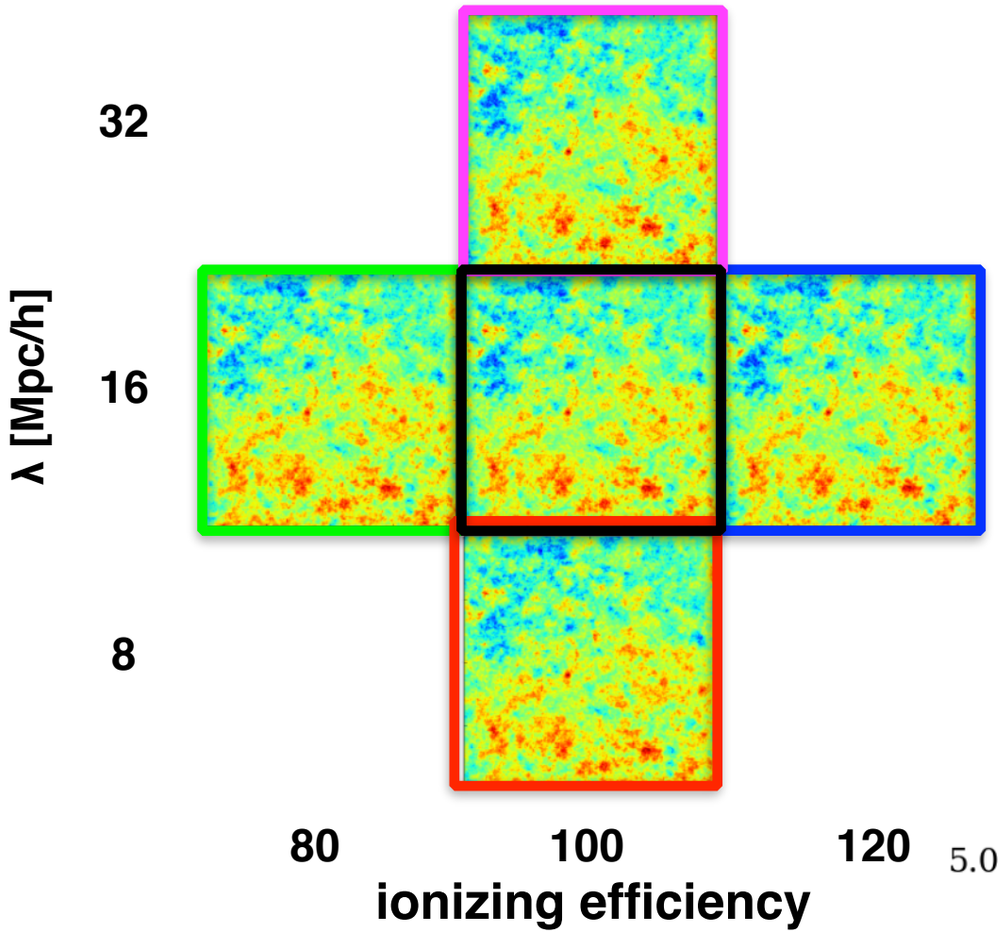


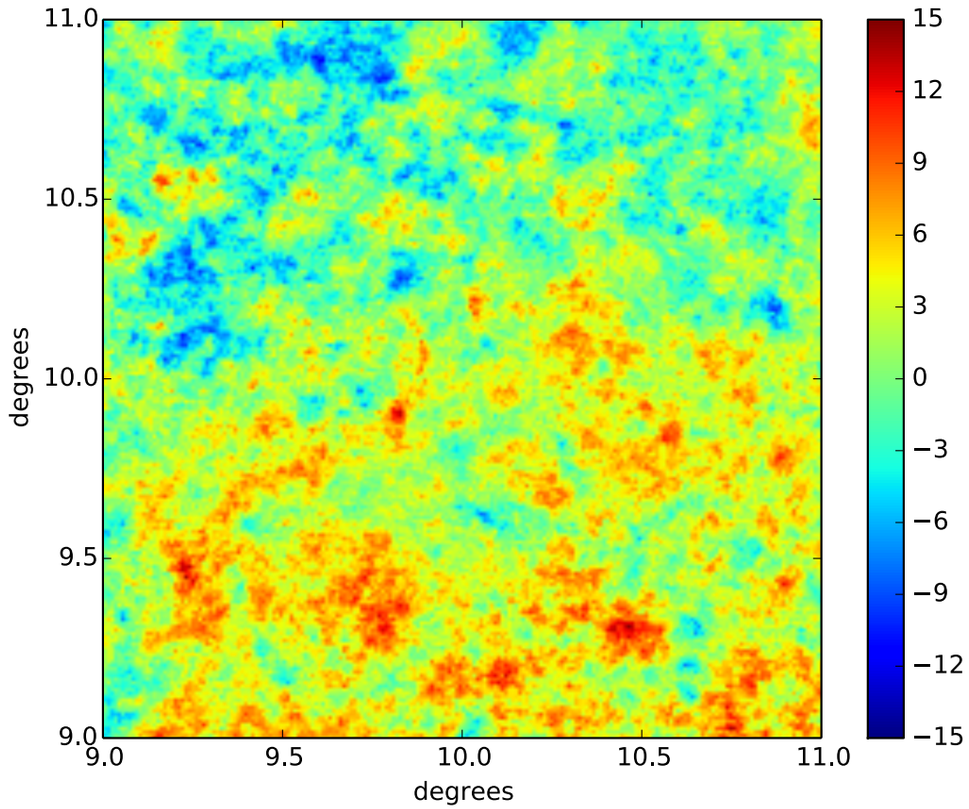


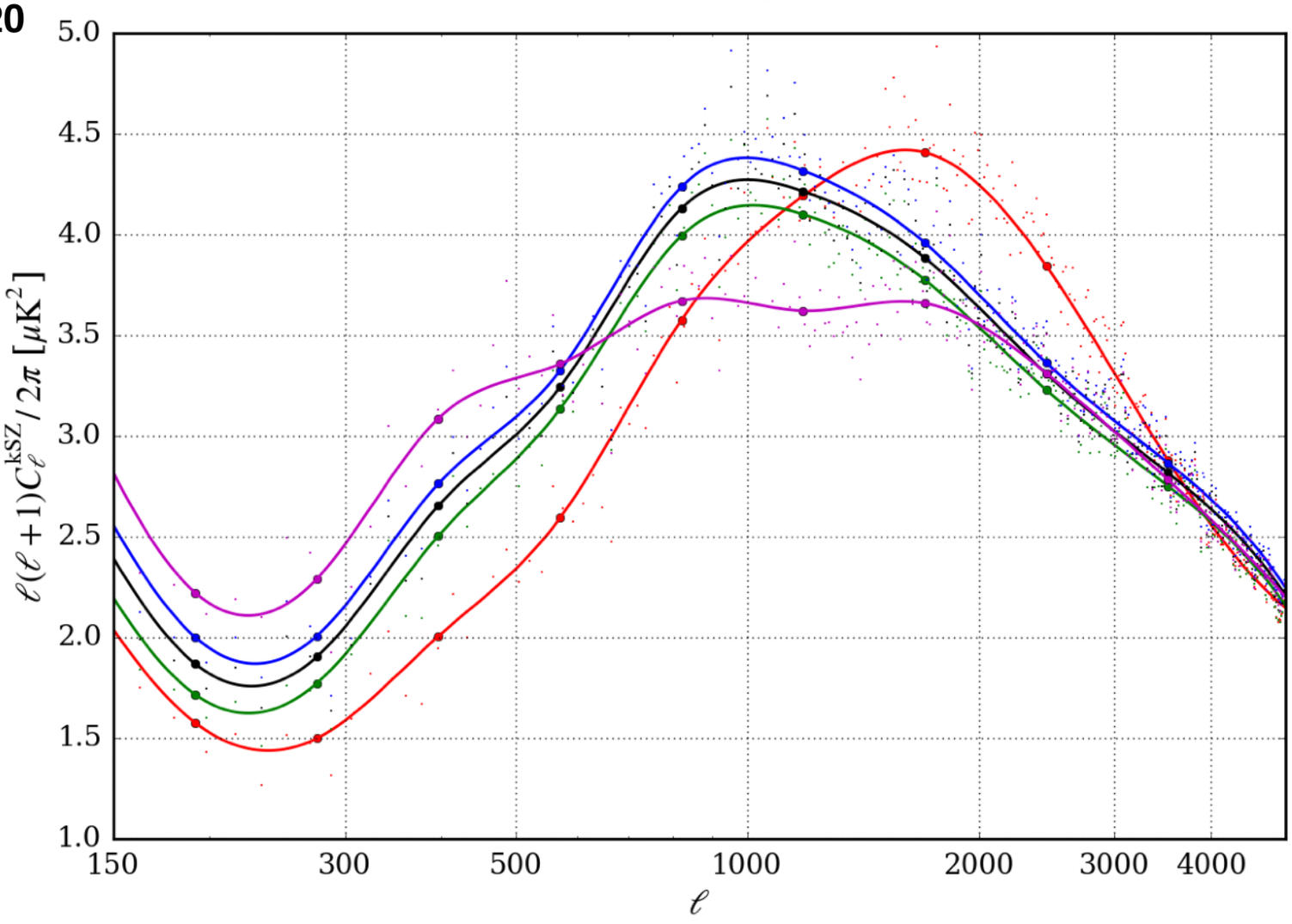






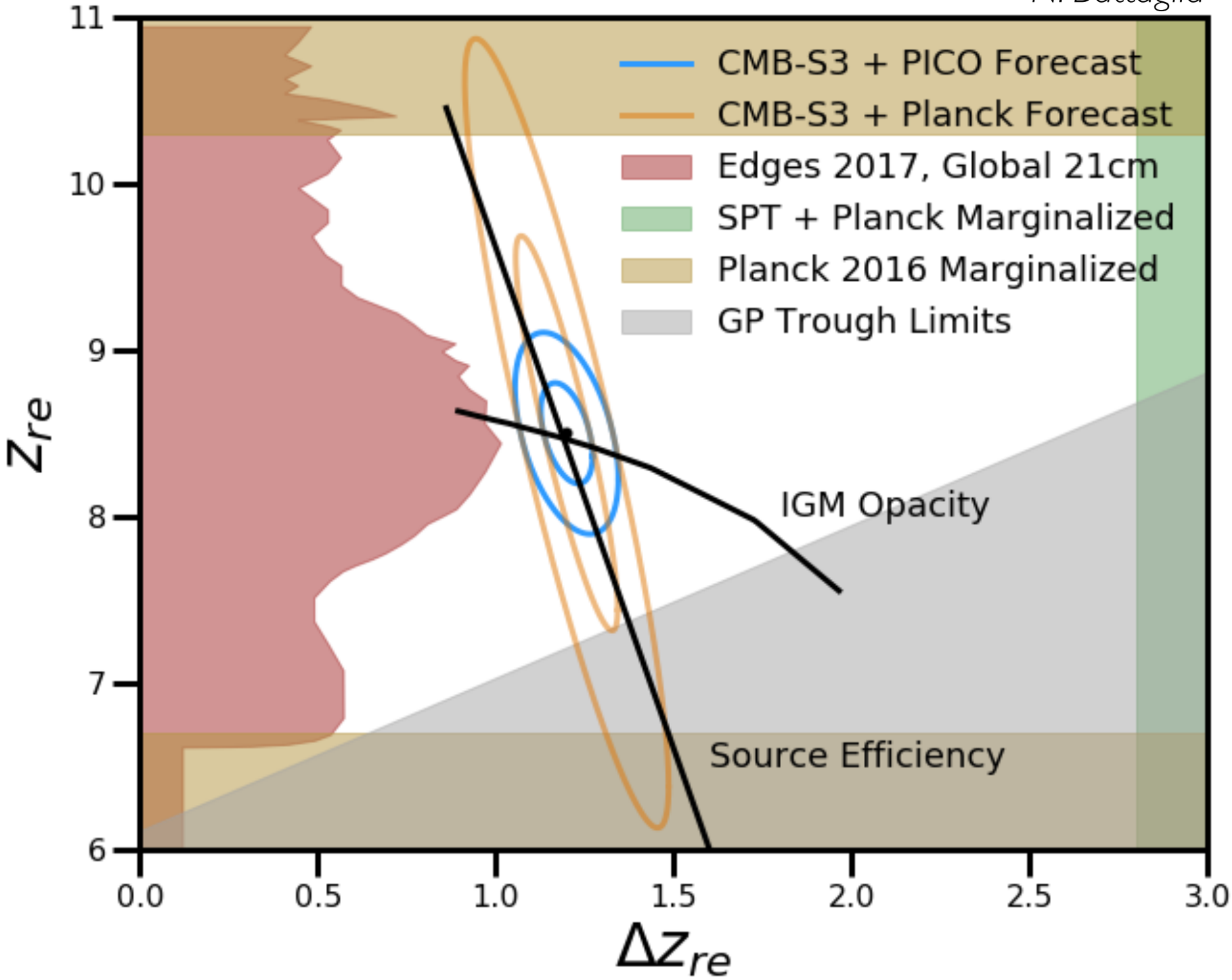

32
16
8
λ [Mpc/h]
80
100
120
ionizing efficiency


11.0
10.5
10.0
9.5
9.0
degrees
9.0
9.5
10.0
10.5
11.0
degrees
15
12
9
6
3
0
−3
−6
−9
−12
−15

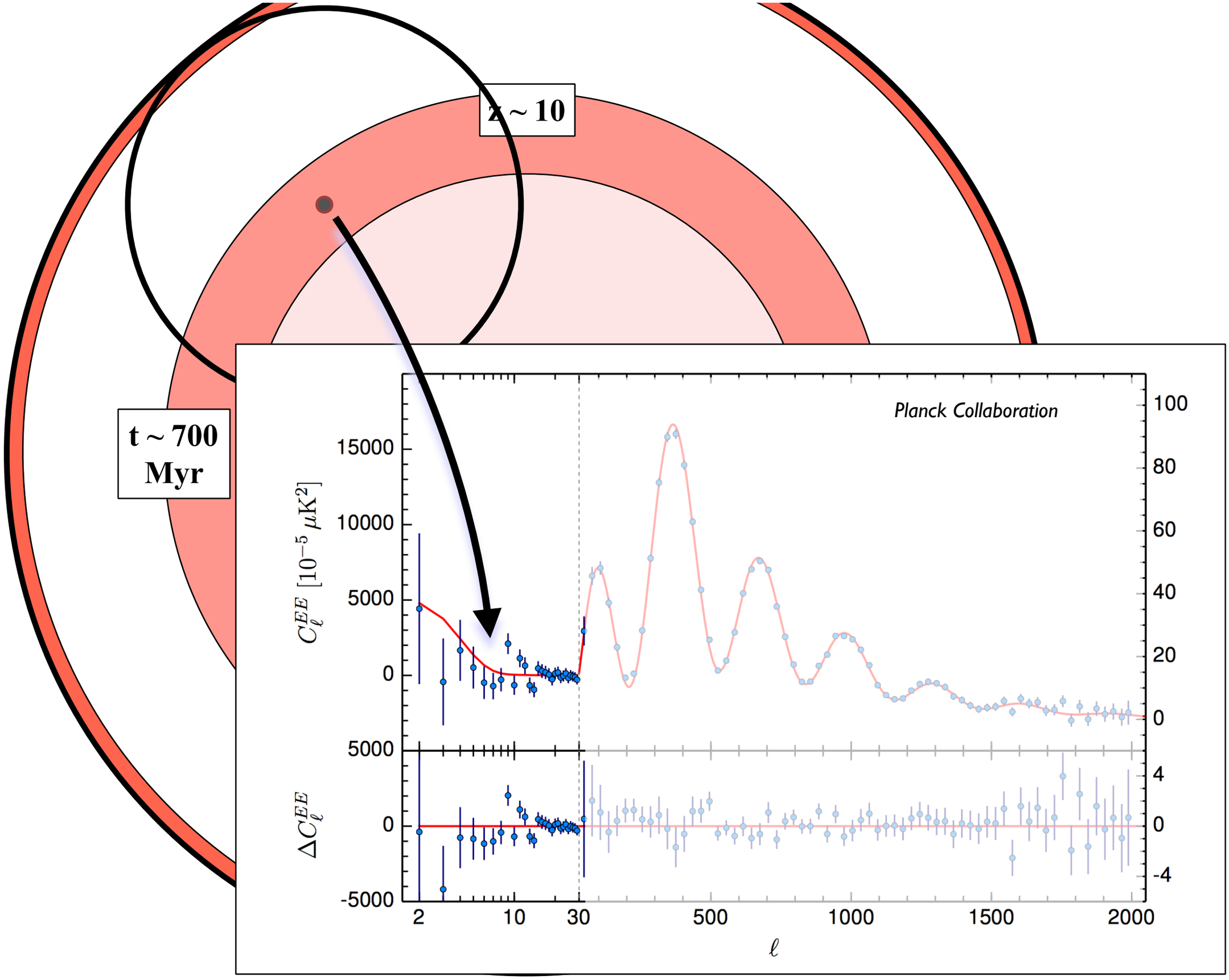

5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
$\ell(\ell+1)C_\ell^{\rm kSZ}/2\pi\ [\mu{\rm K}^2]$
150
300
500
1000
2000
3000
4000
ℓ

Learning About Reionization with a τ Measurement

N. Battaglia



Beyond τ with the Reionization Bump



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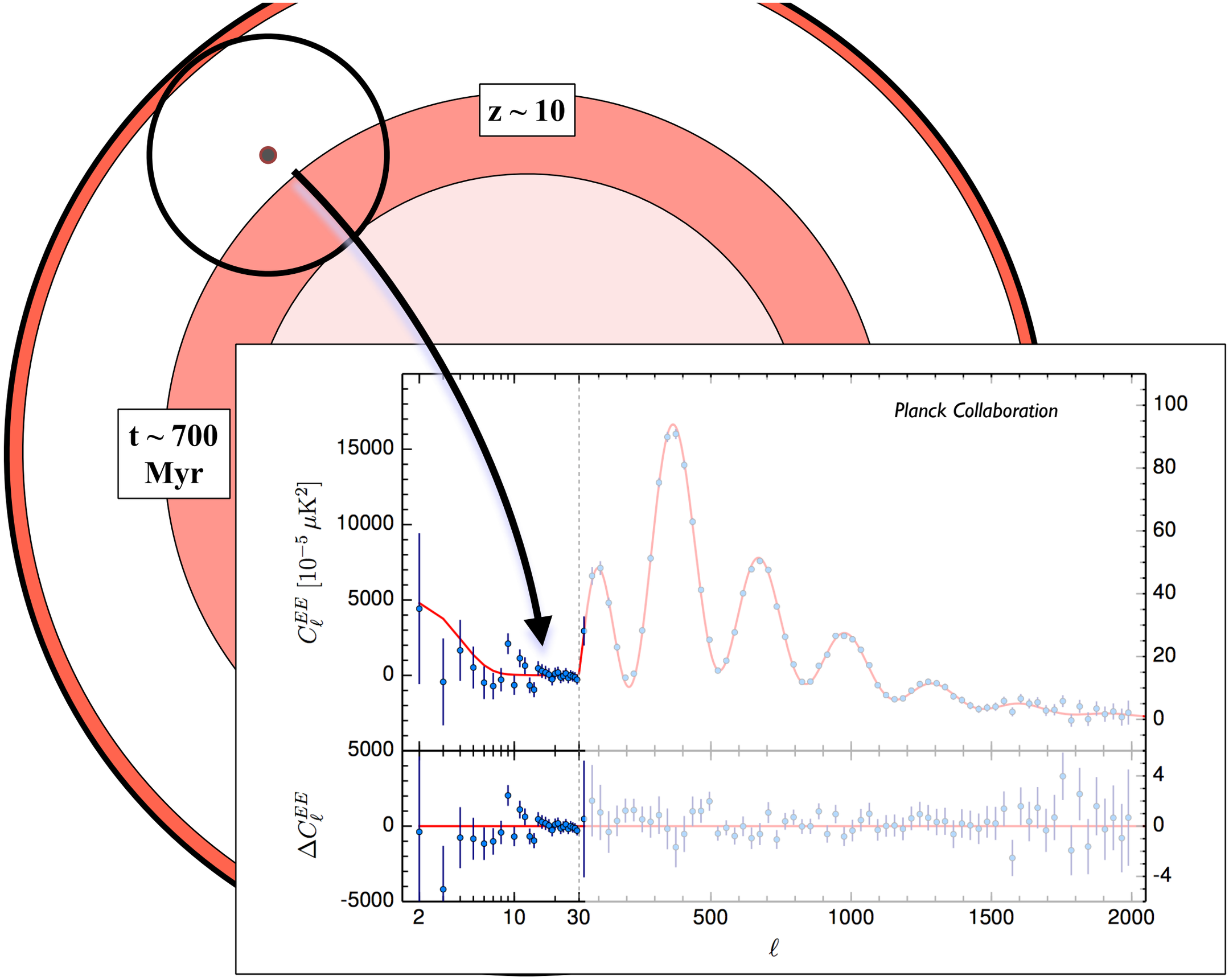

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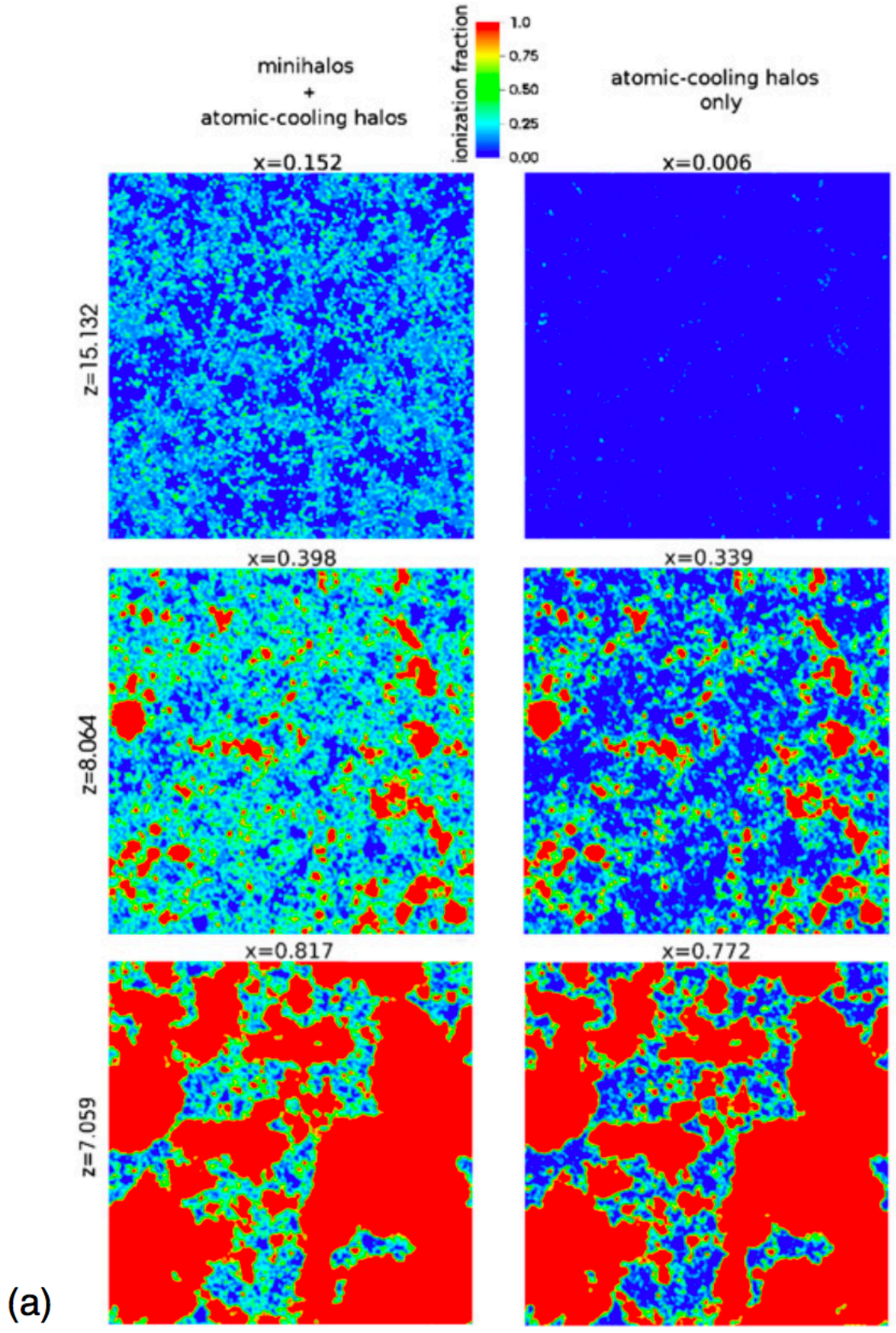
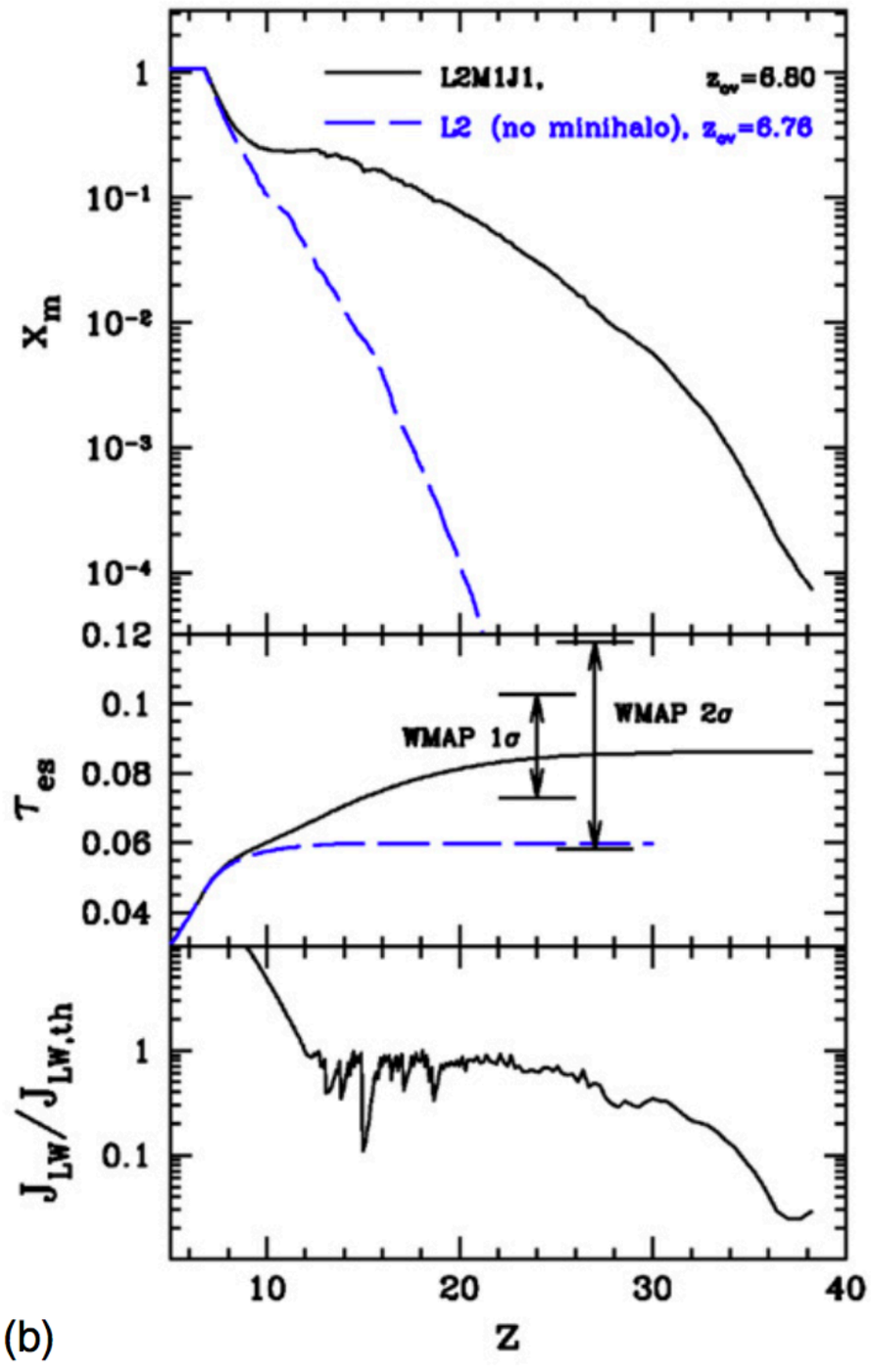
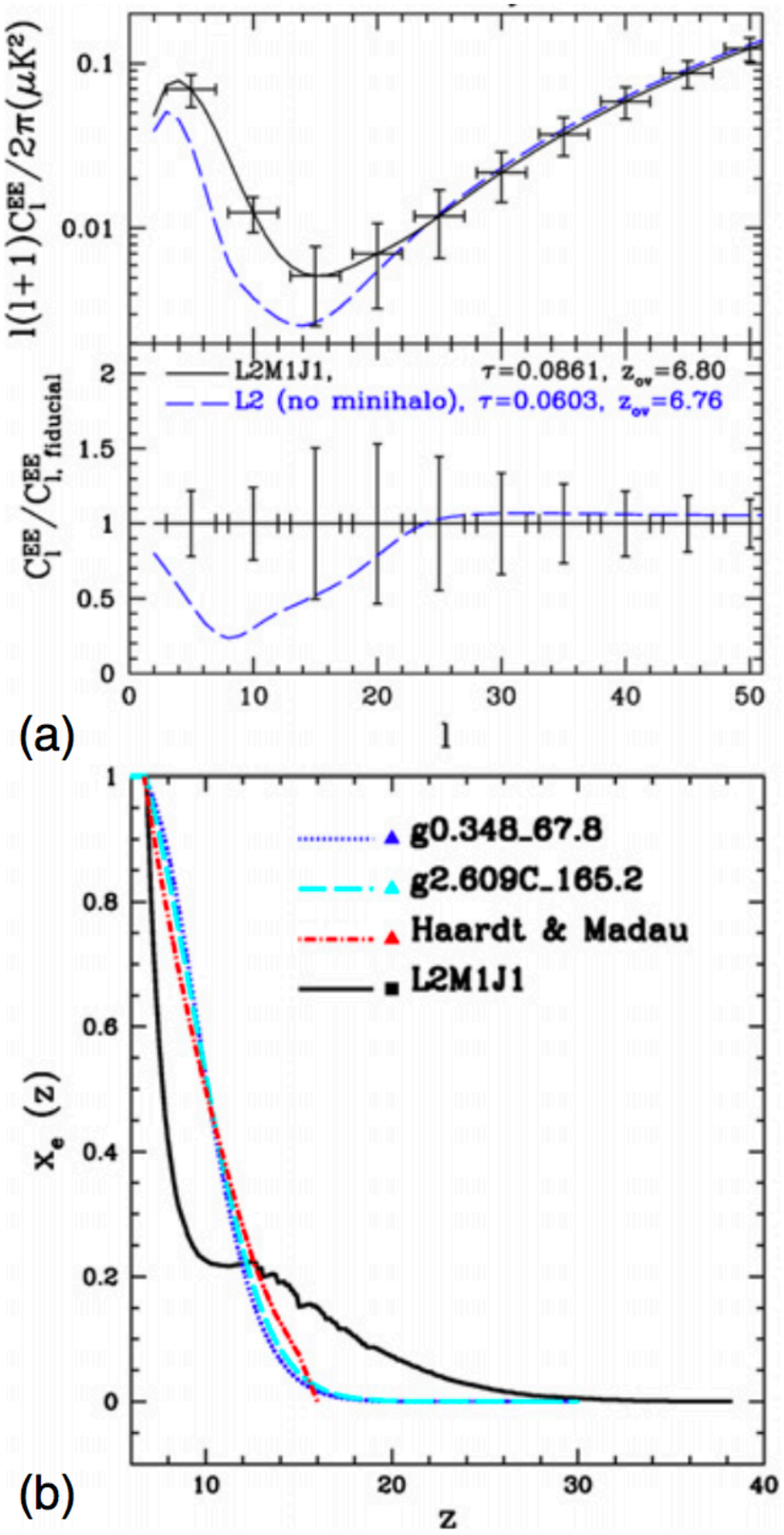
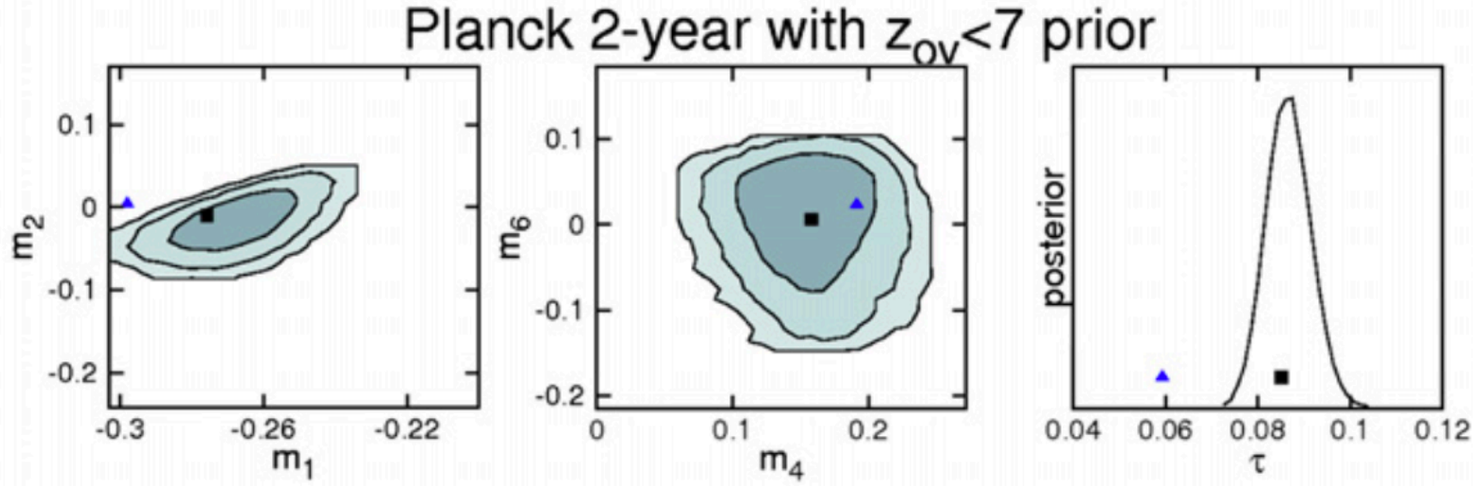


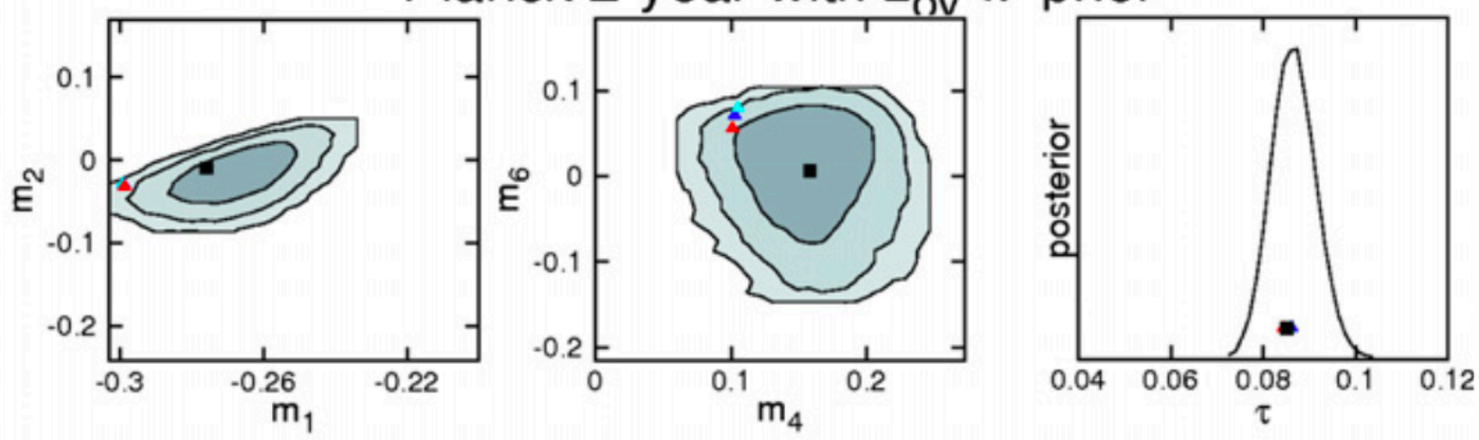


Ahn et al. (2012)

Beyond τ with the Reionization Bump



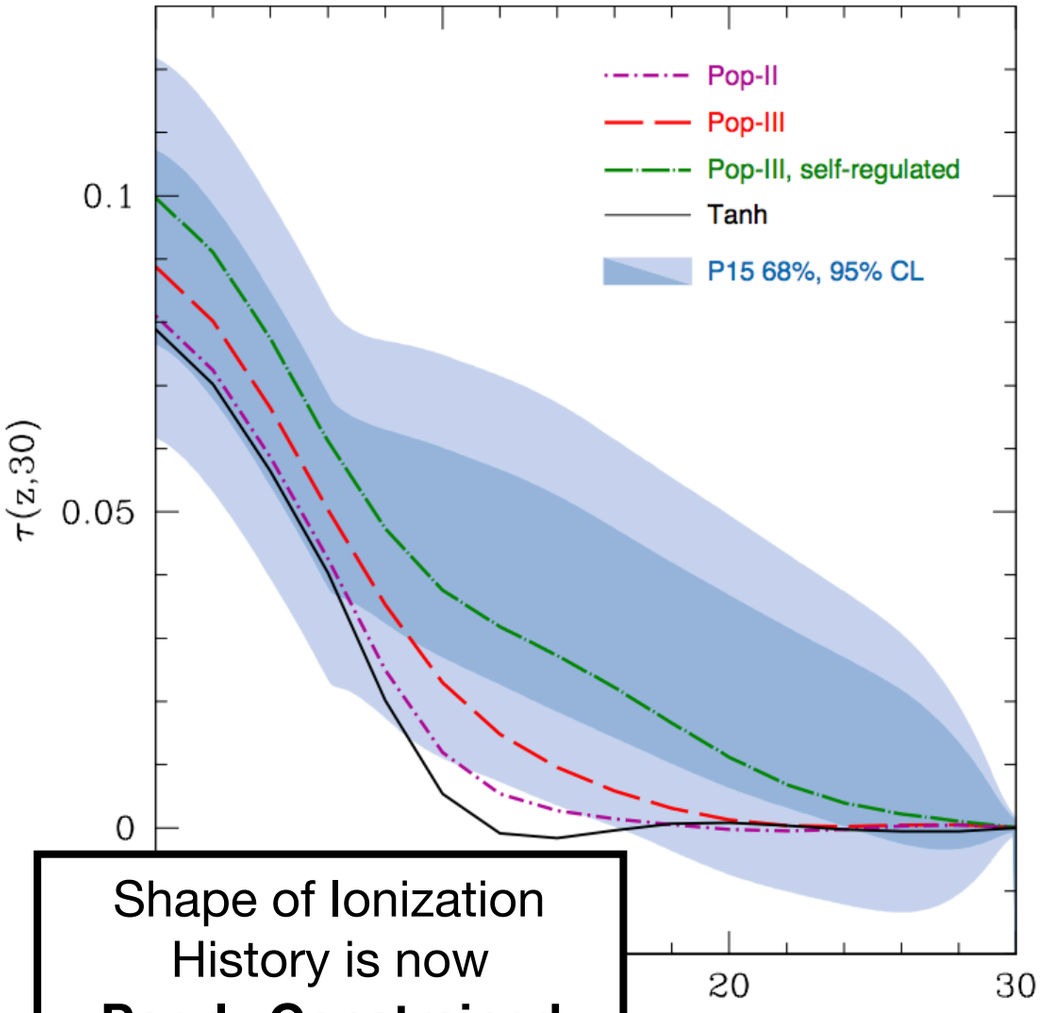




Ahn et al. (2012)

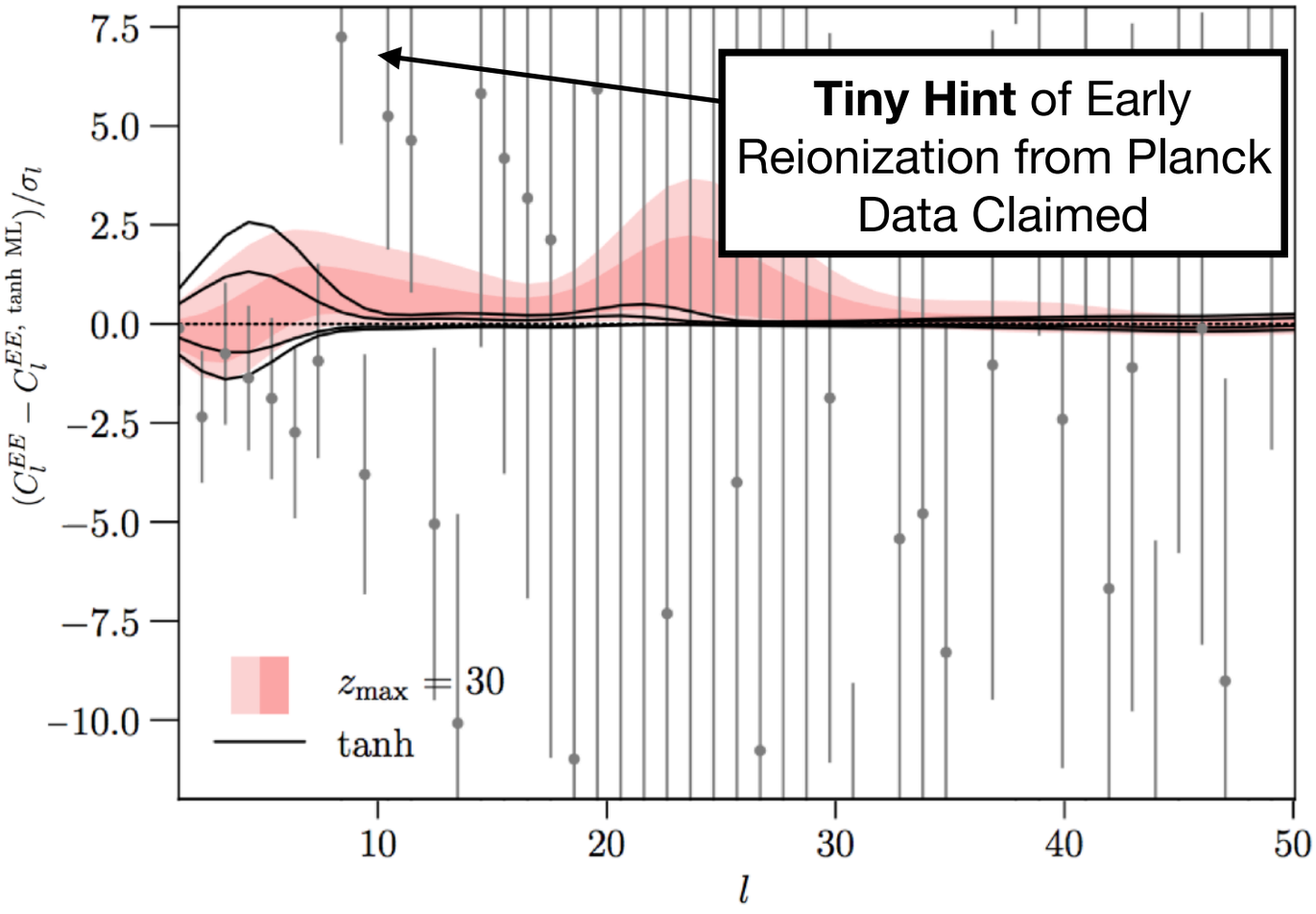
Beyond τ with the Reionization Bump

Miranda, Lidz, Heinrich & Hu (2017)



Shape of Ionization History is now **Poorly Constrained**

Heinrich & Hu (2018)



Beyond τ with the Reionization Bump

Heinrich & Hu (2018)

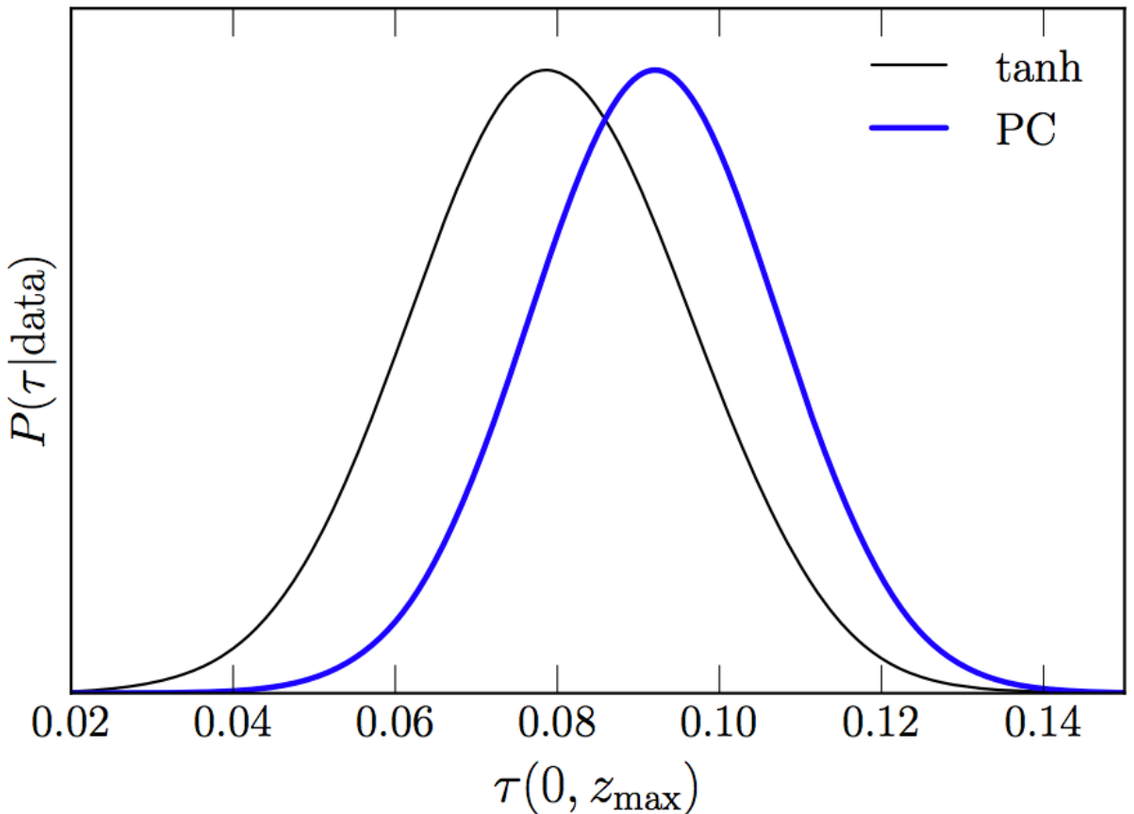
TABLE I. Total and high redshift optical depth constraints for different analyses of Planck 2015 data.

Model	$z_{\rm max}$	$\tau(0, z_{\rm max})$	$\tau(15, z_{\rm max})$	$\tau(30, z_{\rm max})$
tanh	...	0.079 ± 0.017	...	...
PC	30	0.092 ± 0.015	0.033 ± 0.016	...
PC	40	0.095 ± 0.016	0.039 ± 0.017	0.013 ± 0.014
PC	50	0.096 ± 0.016	0.040 ± 0.018	0.016 ± 0.014

Small Hint of Early Reionization from Planck Data Claimed

Shape of Ionization History is now **Poorly Constrained**

Heinrich & Hu (2017)



Beyond τ with the Reionization Bump

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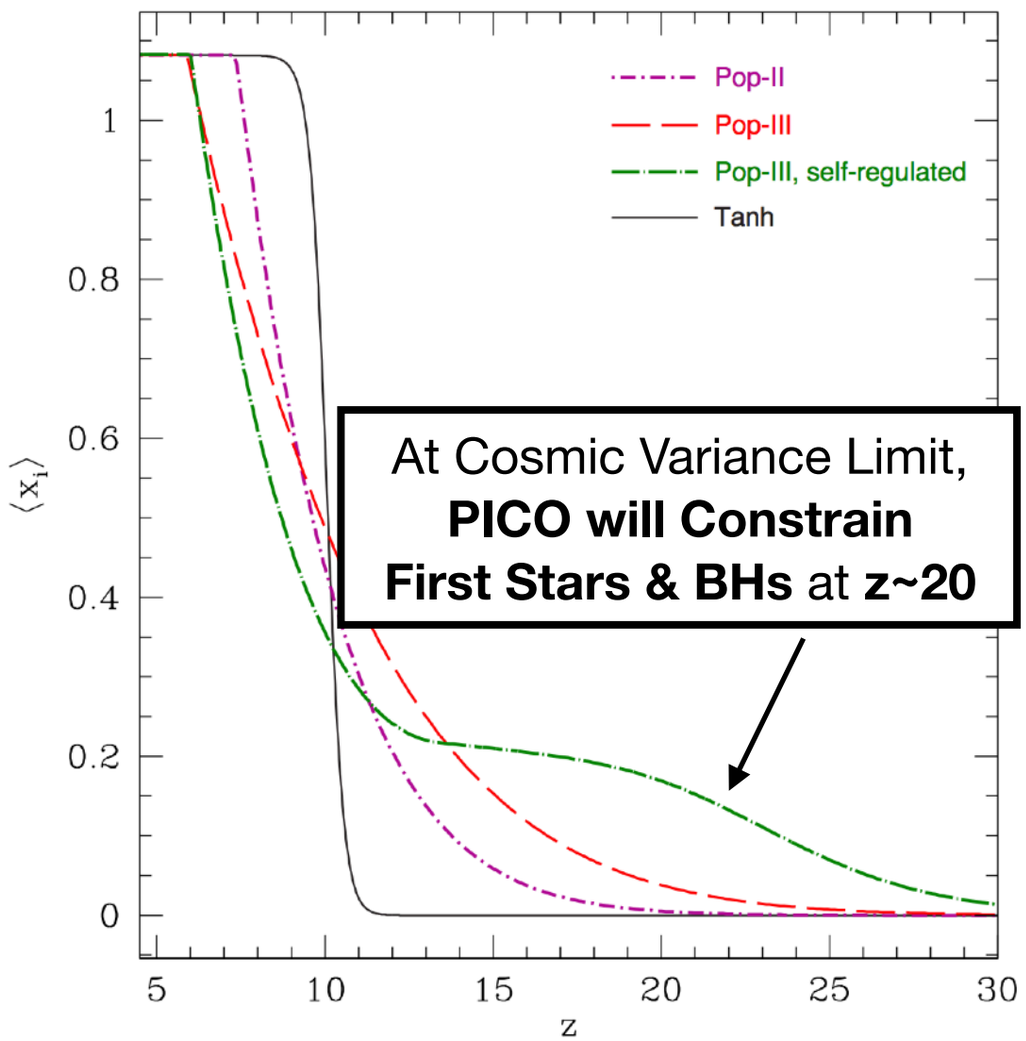
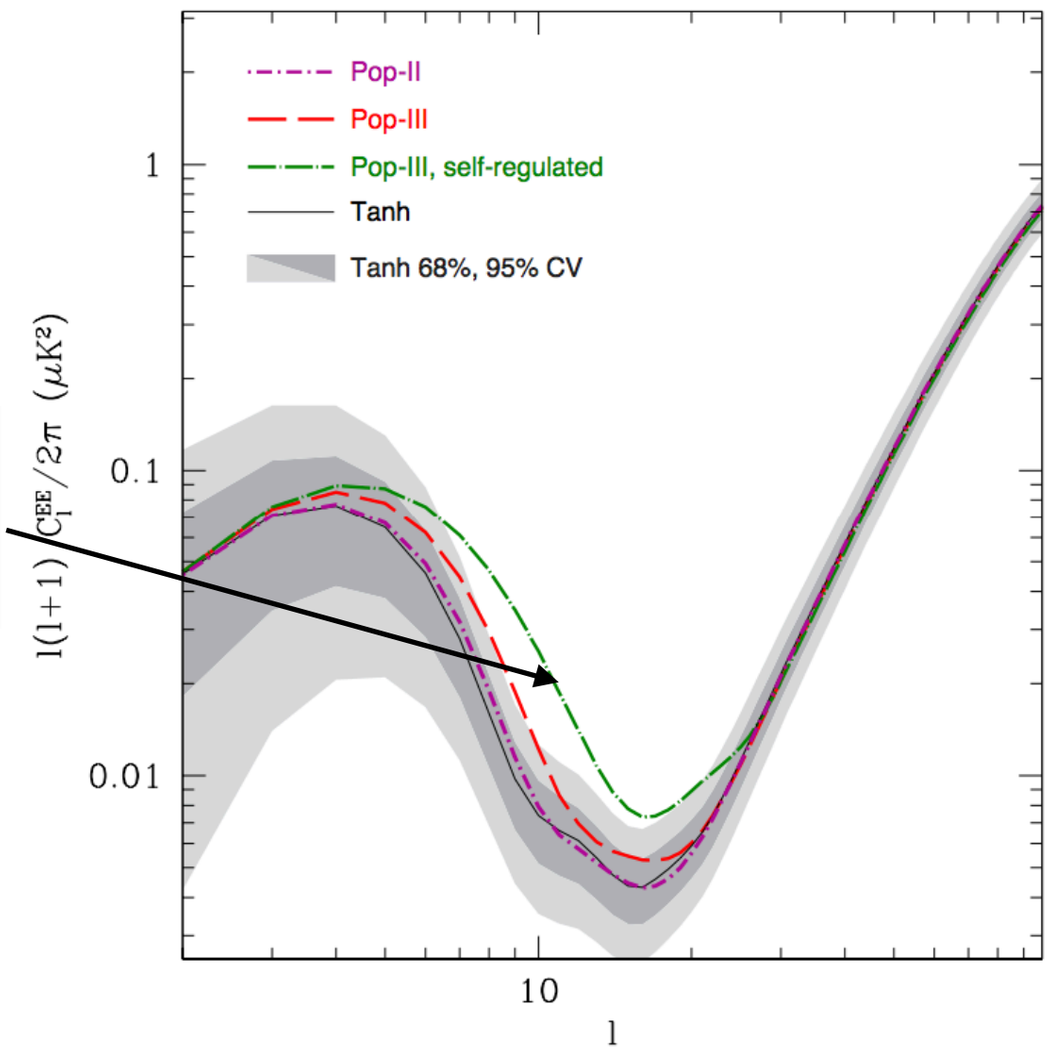
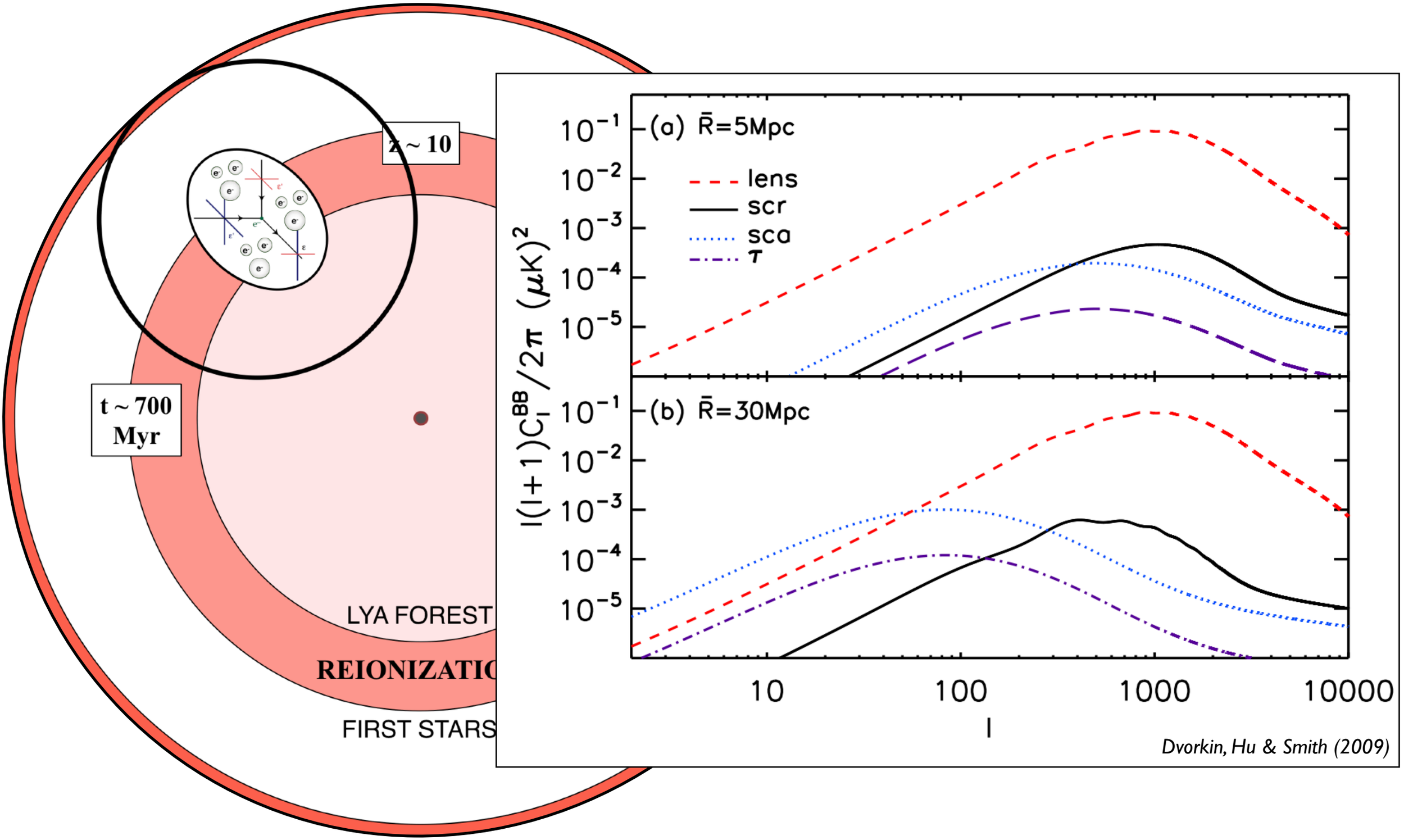




Probing Reionization with Patchy Screening & Scattering



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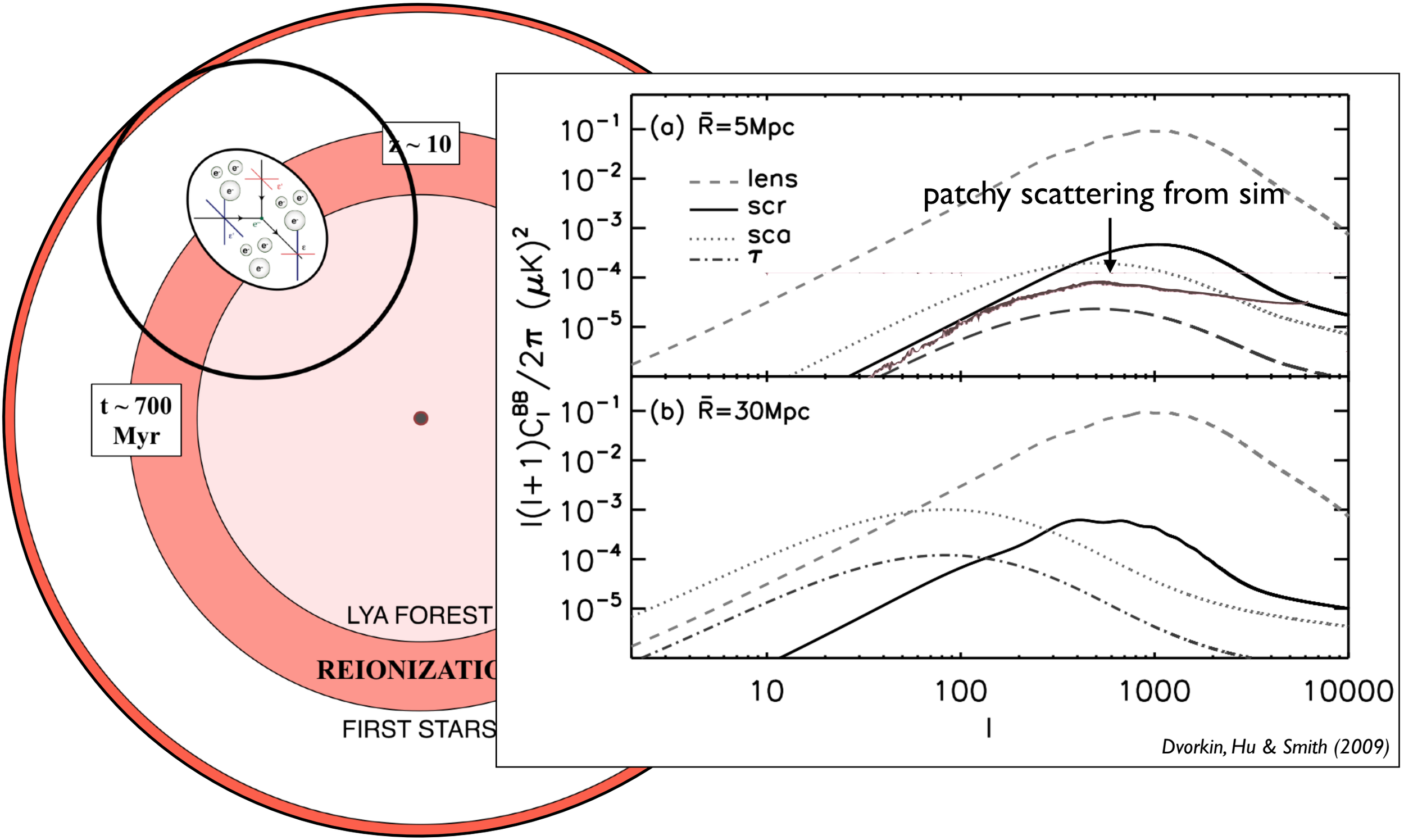

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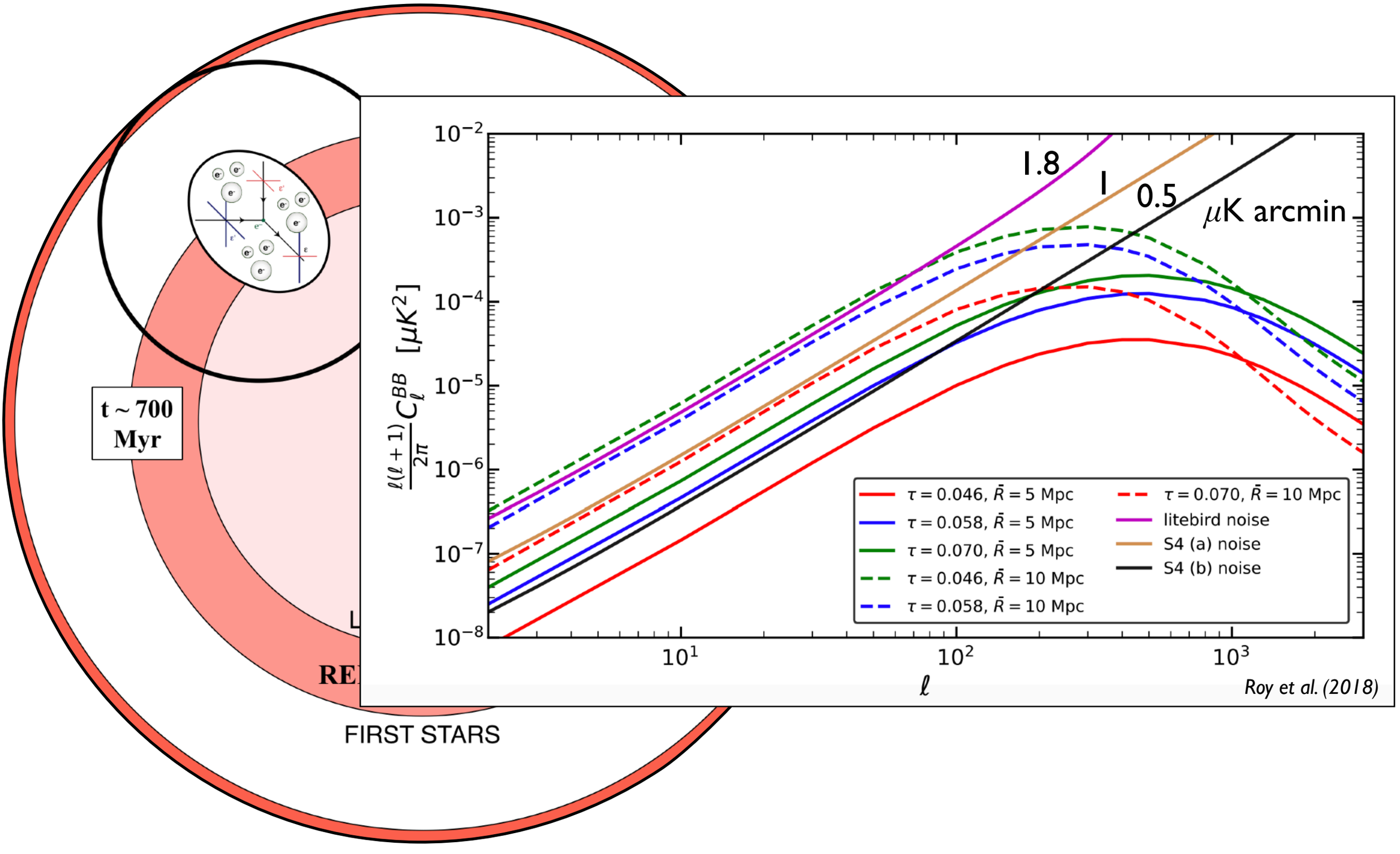
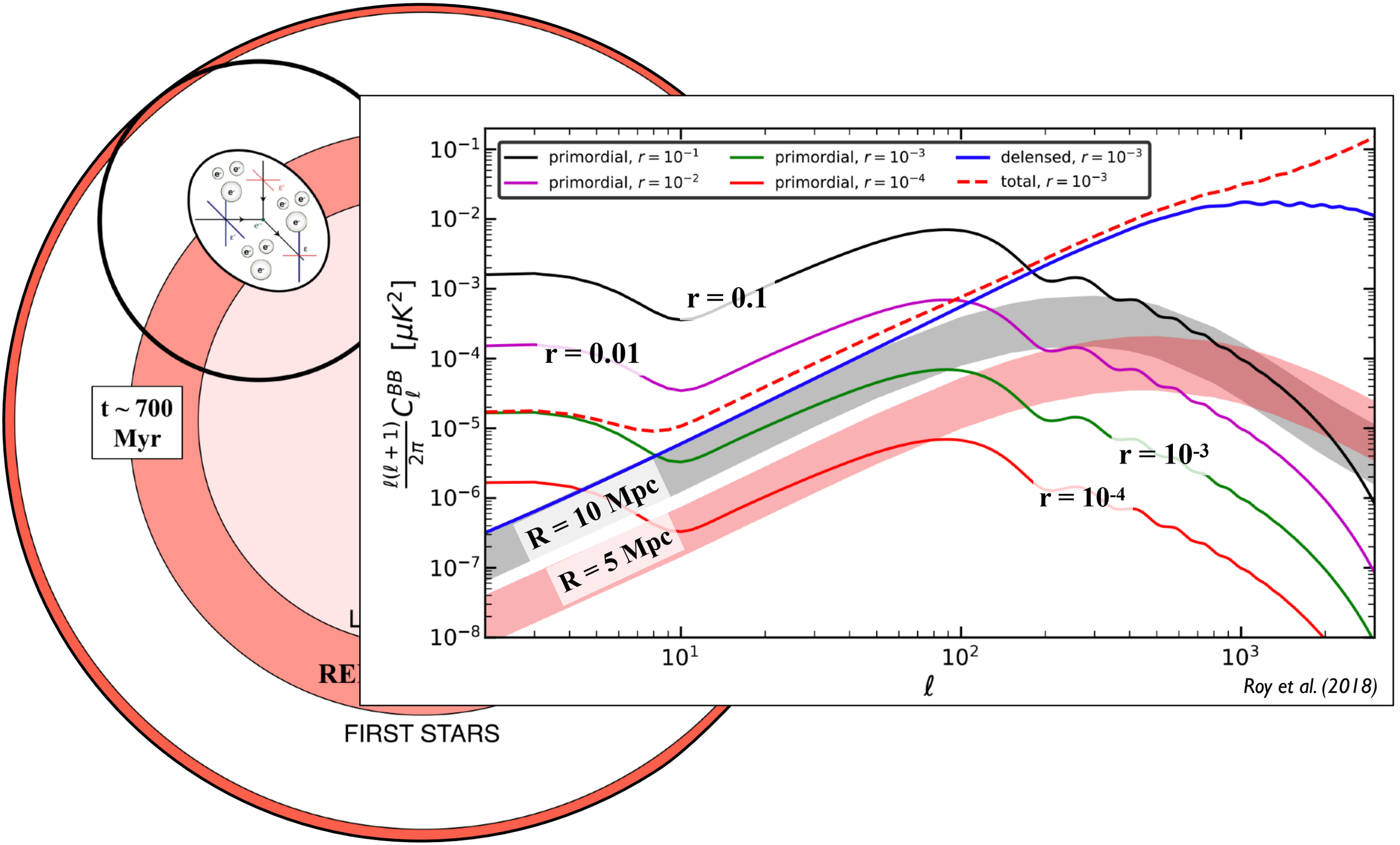


Roy et al. (2018)

Probing Reionization with Patchy Screening & Scattering



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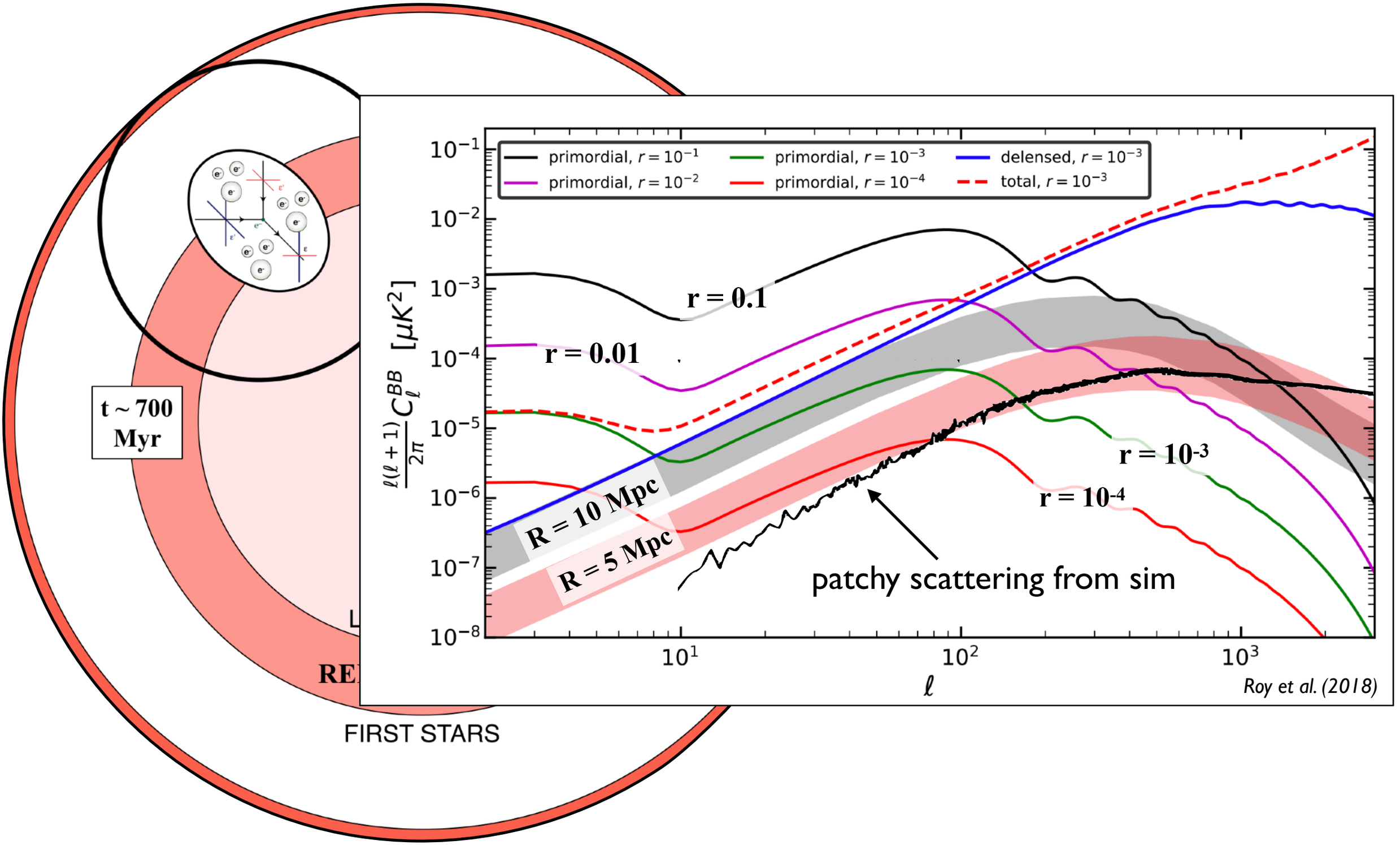

Summary

Reionization bump is an essential probe of reionization and is highly complementary to kSZ, screening, and, 21-cm

Cosmic variance limited measurement could reveal early ionization at z > 15 even with $\tau \sim 0.08$ and reionization ending at z ~ 6

PICO could possibly detect Patchy reionization at $\ell \sim 100$ and probe its characteristic scales

B-modes from quadrupolar scattering of τ-fluctuations induced by reionization may contaminate the primordial signal with a bias at the level of $r \sim 10^{-3}$

Joint Simulation and Modeling of the reionization bump, patchy screening, and 21-cm can mitigate the effect of patchy scattering as a foreground